ARR No. 3L01

JAN 30 1947

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

# WARTIME REPORT

ORIGINALLY ISSUED

December 1943 as
Advance Restricted Report 3L01

## FATIGUE STRENGTH AND RELATED CHARACTERISTICS OF SPOT-WELDED JOINTS IN 24S-T ALCLAD SHEET

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WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

# FATIGUE STRENGTH AND RELATED CHARACTERISTICS OF SPOT-WELDED JOINTS IN 24S-T ALCLAD SHEET

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## SUMMARY

The investigations on spot-welded 24S-T alclad reported here lead to the following conclusions:

1. For lap-joint samples with a single row of spot welds, the static ultimate strength in pounds per inch of joint shows a maximum with varied spot spacing at a spacing of about 3/4 inch. On the contrary, the load sustained to a given lifetime in fatigue increases as the spot spacing decreases from $1\frac{1}{4}$ inches to 3/8 inch.

2. Lap-joint samples spot-welded by different companies showed variation in static strength as high as 20 percent and variations in fatigue strength as high as 35 percent. The variation in fatigue strength showed no correlation with variation in static strength. The spot welds in these samples differed considerably in shape as well as in size.

3. Tests on a few wire-stitched lap-joint samples showed that some of these with 8 to 12 staples had higher fatigue strengths than samples with 11 spot welds.

4. The fatigue strength of stiffened panels tested in compression shows a decrease of as much as 50 percent for an increase in spot-weld spacing from 3/4 inch to 2 inches. There is little correlation between the variation of fatigue strength and that of static strength.

5. Heat-cracked welds in stiffened panels were generally as strong in both static tests and fatigue tests as sound welds. The transverse cracks from overheating the welds did not, in general, incept fatigue failure.

# INTRODUCTION

The following progress report on the Fatigue Characteristics of Spot-Welded 24S-T Alclad Aluminum Alloy includes the results of several miscellaneous tests which are extensions of previous work. The previous investigation is completely described in a report published by the National Advisory Committee for Aeronautics as Advance Restricted Report ARR No. 3F16 (hereinafter referred to as reference 1).

The present progress report is divided into five parts. Part I gives the results of tension fatigue measurements on lap-joint samples with a single row of spot welds spaced 3/8 inch apart. This extends the previous work which included samples with spot spacings of 3/4 inch and 1¼ inches so as to allow some conclusions concerning the effect of spot spacing on fatigue strength.

All spot welding on samples used in the previous investigation and on those concerned in part I of the present report was done at the Rensselaer Polytechnic Institute. It seemed desirable to compare fatigue strengths of samples spot-welded by different companies under commercial conditions. Part II of this report contains data on lap-joint samples welded at two different companies and a comparison of these data to values obtained in the earlier work on samples from the Rensselaer Polytechnic Institute.

Part III contains some results on fatigue strengths of wire-stitched lap-joint samples and a comparison of these results with values for spot-welded samples.

The work previously reported also included compression fatigue tests on panels spot-welded to hat-shape stiffeners. Part IV of this progress report contains data on similar samples with spot spacings of 2 inches in extension of the spacings of 3/4 inch and of 1¼ inches previously used. Comparison of the various results allows some conclusions concerning the effect of spot spacing on compression fatigue strengths of stiffened panels.

Part V contains results of compression fatigue tests for stiffened panels with purposely overheated spot welds. Comparison of these data with values obtained earlier for samples with sound welds shows the effect in these tests of heat cracking in spot welds.

The general routine of testing for all samples concerned here is the same as that used in the previous investigation. (See reference 1, appendix II.) Briefly, tests were made on Krouse Direct Repeated Stress Machines, and load values were corrected for dynamic inertial effects by the use of electrical strain gages. Load values were set and maintained to about ±15 pounds or to 3 percent. Samples were checked by frequent periodic inspection.

This investigation, conducted at the Battelle Memorial Institute, was sponsored by, and conducted with financial assistance from, the National Advisory Committee for Aeronautics.

Acknowledgment is due Mr. E. S. Jenkins of the Curtiss-Wright Corporation and Dr. Maurice Nelles of the Lockheed Aircraft Corporation for advice and assistance in obtaining materials and jointed samples for this investigation. Many of the test pieces were spot-welded at the Rensselaer Polytechnic Institute through the courtesy of Dr. Wendell F. Hess.

## I. LAP-JOINT SAMPLES WITH 3/8-INCH SPOT SPACING

### Materials, Test Pieces, and Static Tests

Tests reported here were run on samples made from 0.040-inch thick 24S-T alclad sheet. The properties of the sheet material itself have been tested sufficiently to insure that it is representative of its class of materials. (See reference 1, table 1.)

A representative fatigue test piece is illustrated in figure 1. The sample was made by joining two pieces, each 9 inches long by 5 inches wide, by a single row of spot welds across the center of a 1-inch overlap. Each sample had 11 spot welds spaced 3/8 inch between centers. The spot welding was done at the Rensselaer Polytechnic Institute and their information concerning surface preparation and spot-welding conditions is summarized in table 1.

Static tests of single-spot coupons were made at R. P. I. Static tests on actual multispot samples were made at Battelle on a 20,000-pound Baldwin Southwark testing machine using the same grips and loading technique as for the fatigue tests. The resulting data are given in table 2.

## Examination of Spot Welds

Figure 2 illustrates typical spot welds sectioned from untested samples. Structurally, these welds resemble those on similar samples with wider spot spacings. (See, for example, reference 1, fig. 14.) The welds show an almost rectangular cross section in contrast to welds made in other laboratories and shown in figures 9 and 10.

Careful measurements of various weld dimensions have been made. To avoid any misunderstanding, the following are definitions of the quantities measured:

(1) Percent penetration: the maximum cross section of the weld in a direction perpendicular to the sheet divided by twice the original sheet thickness

(2) Indentation: the maximum reduction of cross section at the weld center

(3) Offset: the difference between the penetration of the weld slug in one sheet from the center and its penetration in the other sheet

Figure 3 is a labeled sketch of a cross section of a spot weld and shows the various structural zones as well as the geometrical significance of the quantities defined above.

Micro-hardness measurements were taken on an Amsler-Vickers machine using a $1\frac{1}{2}$-kilogram load and a $136^{\circ}$ diamond penetrator. This was done as a start in studying the relative physical properties of various structures in the spot weld.

Table 3 summarizes the data obtained by such measurements on spot welds of untested samples.

## Fatigue Tests

Fatigue tests were taken in repeated tension from a maximum load to a minimum load at about 1500 cycles per minute. Three sets of data were obtained at three ratios of minimum load to maximum load (0.25, 0.50, and 0.75).

Load was maintained by periodic checking until failure. The cut-off was set so that a drop of 300 pounds or less would stop the machine. In all cases, this drop occurred only when the sheets completely separated or when a crack had spread nearly across one sheet.

Table 4 gives the results obtained. As noted previously for other samples, there were three types of failure: shearing of the welds at very high loads, "pulling buttons" at lower loads, and fatigue cracking across a line of welds at all low loads. These are noted in the table. (Examples are shown in reference 1, figs. 1A to 1D.)

Figure 4 shows load-life curves plotted from these data. The general appearance of the curves is like that previously noted (reference 1, figs. 6 and 7) for test pieces with larger spacings between spot welds.

## Examination of Failures

Fatigue failures occurred in the same manner as previously noted for similar samples with wider spot spacings. Cracks started at the projection of the internal alclad into the weld, and proceeded fanwise toward the external alclad. Figure 5(a) illustrates this.

In all cases in which a wide variation of spot-weld dimensions was noted on a single sample, failure first occurred at the smaller and thinner of the two outside welds. Figure 5(b) shows the first and the eleventh welds of a sample in which a crack started at the first spot and failure occurred before this crack reached, or another crack started, at the eleventh spot.

## Discussion of Results and Conclusions

Figure 6 shows load-life curves for three sets of 0.040-inch thick lap-joint samples with three spot spacings. (The curves for spacings of 3/4 inch and of 1¼ inches are taken from reference 1.) It should be noted that the data are plotted in terms of pounds per inch of joint. Thus the total fatigue strength of a joint with 3/8-inch spot spacing is greater than that of a joint with 3/4-inch spacing, although the strength per spot is less for the smaller spacing. The curves in figure 6 are for a load ratio of 0.25; similar curves for ratios of 0.50 and of 0.75 show little of additional interest. For all load ratios and over the whole load range tested, samples with smaller spot weld spacings had higher fatigue strengths.

The dependence of fatigue strength on weld spacing is shown directly in figure 7 for several lifetimes and at three ratios. Note that the static ultimate is highest for the 3/4-inch spot spacing and drops off for the 3/8-inch spacing.* Apparently this is another example of the situations in which fatigue strengths cannot be predicted from static tensile tests.

Figure 8 presents another view of the same data. In this figure, values of the ratio of static ultimate strength to fatigue strength at a load ratio of 0.25 are plotted against the number of cycles to failure. Thus the ordinates represent a kind of "fatigue sensitivity" of the samples. The nonlinear shapes of these curves and the variation with spot weld spacing (note the "cross-over" of the curves for 3/8 in. and for 1¼ in. spacings) present more evidence of the difficulty of predicting fatigue strengths from static strengths.

In summary, the data on samples with 3/8-inch spot spacings and those on samples with wider spacings afford these conclusions:

1. Fatigue failures for samples with 3/8-inch spot weld spacings were like failures reported for samples with wider spacings.

2. Load to failure in pounds per spot decreases with decreasing weld spacing.

3. The data do not allow a clear-cut decision as to the optimum spot spacing, since it appears that the best spot spacing is different for static strength than it is for fatigue strength. The only statement that appears to be warranted at this time is that the best combination of static and fatigue strengths can be secured with a spot spacing between 3/8 inch and 3/4 inch.

4. It seems advisable to determine whether further decrease in spot spacing will further increase the fatigue strengths. Tests proposed with roll welds may serve to answer this question.

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*It is, perhaps, worth noting in fig. 7 that the curve for a lifetime of 10,000 cycles at a load ratio of 0.50 is the most nearly like the curve for static failure. A sample failing at 10,000 cycles at a ratio of 0.50 had a very high <u>mean load</u> or <u>high static component</u> of load.

5. There is additional evidence that fatigue strengths are not simply related to static strengths.

## II. LAP-JOINT SAMPLES SPOT-WELDED BY DIFFERENT COMPANIES

### Test Pieces, Spot Welds, and Static Tests

Lap-joint samples similar to those already described (see fig. 1 for illustration) were spot-welded at two companies designated as Company A and Company B. Samples from Company A were of 0.040-inch 24S-T alclad and had spot spacings of 3/4 inch and of 1½ inches. Test pieces from Company B had 3/4-inch spot spacings, but included two sets of samples, one of 0.040-inch, and one of 0.025-inch 24S-T alclad.

The preparations for spot welding and the welding conditions, as furnished by the respective companies, are given in table 5.

Spot welds from various untested samples have been sectioned and examined in the manner described in the preceding part of this report. The structural dimensions of individual spot welds of samples from Company A, of samples from Company B, and of corresponding samples welded at the Rensselaer Polytechnic Institute (reference 1, part I) are given in table 6. The results of static tensile tests on various samples are also included in this table.

In general, the R.P.I. welds are flat and continue the maximum weld penetration nearly to the weld extremities. In size and static strength, they are between the Company A welds and the Company B welds.

Welds from Company B are the largest and have the highest static strength. On the other hand, these welds have an uneven perimeter so that they taper down at the weld extremities. Figure 9 illustrates this.

Welds from Company A are shortest and are the lowest in static strength. The spots are rounded, especially on the side of maximum indentation, so that the welds are offset on this side. Transverse cracking was found on several spots from samples with 3/4-inch weld spacing. Illustrations are given in figure 10.

Micro-hardness studies show that, although the width of the dendritic area varies, the hardness of this zone is relatively constant (109 ± 2 Vickers). However, the center-equiaxed region is softer when there is a wide band of dendrites (as in the spot welds from Company A). The Vickers hardnesses of the sheet material are: for R.P.I. samples, 132; for Company B samples, 138; for Company A samples, 142.

## Fatigue Tests

Fatigue tests were run as described for other lap-joint samples. Failure corresponded to a drop in load of about 300 pounds. This drop was usually sudden and was such that, when the load was restored, the sample would hold the restored load for but a few cycles.

The results of fatigue tests on samples spot-welded at Company A are given in tables 7 and 8. Test results for samples from Company B are recorded in tables 9 and 10.

Load-life curves plotted from the data in tables 7, 8, 9, and 10 are shown in figures 11, 12, and 13. In each case, maximum load in pounds per inch of joint is plotted against the number of cycles to failure.

## Examination of Failures

Fatigue cracks were located in the same region in all of the welds examined. Failure started at the protrusion of the alclad into the weld. However, the area surrounding the starting point and through which the cracks propagated had different structural properties in the different types of welds.

In the R.P.I. welds, each spot was of relatively even penetration along its diameter and the internal alclad penetrated well into the spot. Accordingly, the fatigue crack propagated through the dendritic region of the weld.

In the commercial spot welds, the penetration was not so even along a diameter. In general, the cross section perpendicular to the sheet showed a tapering of the weld at each end. Moreover, for these welds, the internal alclad did not protrude far into the spot. Consequently, the fatigue crack did not propagate far through the dendritic structure. Sometimes it even followed the outer perimeter of the weld. Figures 14 and 15 illustrate fatigue failures in welds made by Company A and in welds made by Company B.

In the investigation of the R.P.I. spot-welded samples (see reference 1), there seemed to be some correlation between percent penetration and fatigue strength. For the commercial welds, no such correlation has been found. It is not surprising that penetration measured at the center of a tapered and/or offset weld should have little correlation with fatigue failures which occur at the extremity of the weld.

Micro-hardness values are shown in figure 16. These show two general results. First, the protrusion of the alclad where failure starts is the softest region in the area of failure. Second, there is no drastic hardness gradient between the dendritic region and the heated area surrounding the weld button.

Two factors which seemed to bear a relation to the fatigue strength were (1) extent of the alclad protrusion into the weld and (2) the amount of spot offset. Generally, the greatest alclad protrusion and the least offset correlated with higher fatigue life.

## Discussion of Results and Conclusions

Figure 17 shows comparisons of fatigue strengths of lap-joint samples of 0.040-inch sheet with spot welds (spaced 3/4 in. apart) made by different companies. The curves are plotted for a load ratio of 0.25. Apparently the R.P.I. welds are strongest in fatigue. Samples welded by Company A (weakest in static tests) and samples welded by Company B (strongest in static tests) are both about 12 percent weaker than samples from R.P.I. up to lifetimes of 1,000,000 cycles. At 5,000,000, the welds from Company B are about 22 percent and welds from Company A about 35 percent weaker than welds from R.P.I.

Another way of looking at these results is indicated in figure 18 in which ratios of static ultimate strength to fatigue strength are plotted against the number of cycles to failure. Up to 1,000,000 cycles, welds from Company B appear more fatigue sensitive and welds from Company A less fatigue sensitive than welds from R.P.I.

Figure 19 shows a comparison of results on samples from Company A to results on samples from R.P.I. for a sheet thickness of 0.040 inch and a spot spacing of $1\frac{1}{4}$ inch. Here it seems generally true that samples from R.P.I. are stronger in both static tests and fatigue tests.

Figure 20 compares results on samples from Company B to results on samples from R.P.I. for 0.025-inch sheet with spot welds 3/4 inch apart. Samples from Company B, although slightly stronger in static tests, are weaker in fatigue.

In summary, the following conclusions may be drawn from comparisons of the results on various spot-welded lap-joint samples:

1. The spot welds from different companies differ considerably in shape and this difference in shape, causing a difference in stress concentration, may be as important as variation in structure in affecting fatigue failure.

2. There was a spread of 35 percent in the fatigue strengths of differently spot-welded lap-joint samples.

3. The variation in fatigue strengths had no simple correlation with the variation in static strengths. In fact, some samples, having higher static strengths than others, had lower fatigue strengths.

## III. LAP-JOINT SAMPLES WITH WIRE STAPLES

### Test Pieces and Static Tests

A few test samples of 0.040-inch 24S-T alclad were made of pieces stitched together with steel wire staples. Each test piece consisted of two sheets each 5 inches wide by 9 inches long. The amount of overlap varied from 0 to 1 inch, the number of staples varied from 4 to 12, and several stitch patterns were used. The 8 types of joint tested are indicated in the sketch of figure 21. Figure 21A is a photograph of the four strongest types of stitching.

The following information concerning the stitched samples was furnished by the makers:

(a) The wire used is 290,000 pounds per square inch tensile carbon steel 0.047 inch in diameter with a 0.003-inch hot-dipped zinc coating.

(b) The average proportional limit per staple is 186 pounds.

(c) The average ultimate strength per staple is 560 pounds in the case of groups E, F, G, and H, and is 480 pounds for groups A and B.

A static test was run at Battelle on one sample of each type. Failure in the static test was either by pulling open the staples or by shear of the staple wires at the sharply bent corners. The static test results are given in table 11.

## Fatigue Tests

Table 12 gives the results of fatigue tests at a load ratio of 0.25 on the stitched samples. Figure 22 shows load-life curves plotted from these data and, for comparison, a curve for 0.040-inch lap-joint samples with spot welds made at the Rensselaer Polytechnic Institute and spaced 3/8 inch apart.

Apparently, stitched samples of types A, C, H, and G have higher fatigue strengths than the spot-welded samples. Stitched samples of types B, D, E, and F have low fatigue strengths. It may be noted that types high in fatigue strength had from 8 to 12 staples. Those of low strength had 4 staples per joint except for type D which alone was characterized by having no overlap.

While the results indicate that many of the stitched samples were stronger in fatigue than the spot-welded test pieces, it should be pointed out that data on multiple rows of spots have not yet been obtained; moreover, no data have been obtained on the possibility that stitched joints might loosen under bending stresses. Other factors in the comparison, such as corrosion effects, should also be investigated before attempting to come to final conclusions regarding the relative merits of stitched and spot-welded joints.

## IV. STIFFENED PANELS WITH 2-INCH SPOT SPACING

### Materials, Test Pieces, and Static Tests

Compression fatigue tests have been run on spot-welded stiffened panel samples. Each test piece consisted of a panel of 24S-T alclad 0.032-inch thick by $4\frac{1}{2}$-inches wide by 15.88 inches long fastened with two rows of spot welds to Curtiss-Wright S3-112-32 hat-shape stringer sections. The stringer sections were made of 0.032-inch 24S-T alclad.

A photograph of a stiffened panel test piece of this kind is shown in figure 27. A diagram of the stiffener section is given in reference 1, figure 16. The sheet material used was tested sufficiently to insure that it had normal properties. (See reference 1, table 12.))

Along each row of welds, the spots were spaced 2 inches between centers except near the ends where spots were located 1/8 inch, 5/8 inch, and $1\frac{1}{8}$ inches from each end. The spot welding was done at the Rensselaer Polytechnic Institute and their information on welding conditions is given in table 13. The welds were sound and were about the same size and shape as in other 0.032-inch stiffened-panel-test pieces. Figure 23, (a,b) shows welds sectioned from untested samples.

Static compression tests were taken on the stiffened-panel samples. For those with the 2-inch spot spacing, the buckling stress was low (5720 lb/sq in.) compared to the values (9630) previously reported for samples with 3/4-inch and for samples with $1\frac{1}{4}$-inch spot spacings. The crippling stress (at which the column collapsed) was 26,100 pounds per square inch for samples with a 2-inch spot spacing, but was 27,100 pounds per square inch for the $1\frac{1}{4}$-inch spacing and 29,500 pounds per square inch for the 3/4-inch spacing. Stress strain curves were identical for the three spacings.

### Fatigue Tests

Details of preparing, loading, and checking samples in the compression fatigue tests are recorded in appendix 2 of reference 1. Attempts were made to obtain axial loading and the ends were fixed. The complete separation of panel from stiffener at any one weld was taken as a criterion of failure. This usually caused a drop in load considerably greater than the 30 pounds to which the cut-off mechanism would respond.

At high loads welds pulled loose without evidence of fatigue cracking, but at low loads failure was preceded by a horizontal crack spreading across the width of the panel. Photomacrographs of failed spot welds are shown in figure 23 (c,d). Fatigue cracks often occurred outside the weld button in the sheet itself or in the heat-affected area around the weld slug.

The buckling in fatigue tests occurred in ridges across the width of the panel between spot welds. This type of buckling pattern was not observed for panels with closer spaced spot welds except at high loads in static tests.

The fatigue data for the panels with 2-inch spaced spot welds are given in table 14. Load-life curves plotted from these data are shown in figure 24. Enough samples were available to obtain some data for load ratios of 0.50 and 0.75 as well as for the ratio 0.25 at which data for other panel sections had been previously obtained. Data for the higher load ratios do not appear to offer any unexpected results.

## Discussion of Results and Conclusions

Load-life curves for 0.032-inch stiffened panels with different spot spacings are shown in figure 25. Curves for 3/4- and for $1\frac{1}{2}$-inch spot spacings are taken from reference 1 (figs. 20 and 21). It is apparent that panels with the 2-inch spot spacing have lower fatigue strengths than panels with closer spot spacings.

Figure 26 shows fatigue strengths plotted against spot spacing for various lifetimes. The ordinates are loads divided by the cross-section area of stiffener plus panel. This figure shows clearly a decrease in crippling stress and the greater rate of decrease in fatigue strength with increase in spot spacing. For the 2-inch spacing, the fatigue strengths at different lifetimes are quite near in value to the stress at which the panel buckles under static compression.

Conclusions from these tests on stiffened panels are:

1. The static crippling stress decreases as the spot spacing is increased from 3/4 inch to 2 inches. The stress at which the panel buckles decreases as the spot spacing is increased from $1\frac{1}{2}$ inches to 2 inches.

2. The fatigue strength (for a given load ratio and to failure at a given lifetime) decreases as much as 50 percent as the spot spacing is increased from 3/4 inch to 2 inches.

3. There appears no simple correlation between the rate of decrease of fatigue strength with increasing spot spacing and the corresponding rate of decrease of static strength.

## V. STIFFENED PANELS WITH HEAT-CRACKED WELDS

### Materials, Test Pieces, and Static Tests

The sheet material used for the test pieces to be discussed has been found to have normal properties for 24S-T alclad. (See reference 1, appendix 1.) Panels were $4\frac{1}{2}$ inches wide by 15.88 inches long and were of three thicknesses, 0.025, 0.032, and 0.040 inch. Stiffeners were Curtiss-Wright SS-112-32 and were made of 0.032-inch 24S-T alclad. Panels were fastened to stiffeners by two rows of spot welds. One set of samples had welds 3/4 inch apart except near each end where spots were 1/8 inch, 5/8 inch, and $1\frac{1}{8}$ inches from the end. Another set had spots $1\frac{1}{4}$ inches apart except near the ends where they were spaced as above. A photograph of a typical test piece is shown in figure 27.

Spot welding was done at the Rensselaer Polytechnic Institute and welds were purposely overheated to produce heat cracking. The welding conditions are given in table 15.

Static compression tests were made for each type of sample and the values are given in table 16. The buckling stress quoted is the load value, at which buckling of the panel was first visible, divided by the total cross-section area of stiffener plus panel. The crippling stress is the load at crippling divided by the total cross-section area. The values for buckling stress and those for crippling stress for the samples with cracked welds agree well with values for corresponding samples with sound welds. (See reference 1, table 14.) Stress-strain curves for samples with cracked welds are identical with those reported for sound welds (reference 1, figs. 18 and 19) and are accordingly not reporduced in this report.

## Examination of the Overheated Welds

Photographs of sectioned spot welds are shown in figures 28 to 31. In general, welds sectioned longitudinally or parallel to the longest dimension were longer than those sectioned transversely. However, this difference was less than that found previously for sound welds. In some cases, welds from samples with 3/4-inch spot spacing were larger than welds from samples with $1\frac{1}{4}$-inch spacing, but there was no great variation of weld size with spacing. Transverse cracks were found in most of the spot welds. The intensity of cracking varied quite widely among the specimen groups.

The welds were smallest and had the least penetration for samples with 0.025-inch sheet. (See fig. 31.) Welds from these samples varied considerably in size and included many sound welds.

Heat cracking was heaviest in spots from the 0.032-inch panels. (See figs. 28 and 29.) These welds were quite uniform in size and in amount of cracking. The size was nearly the same as for sound welds in previous tests.

There was considerable variation in size, penetration, and amount of cracking for welds in the 0.040-inch panels. For these, penetration was often extreme. In some cases, the weld slug had melted clear through to the external alclad, leaving many small checks and blow holes in the weld center. (See fig. 30.)

## Fatigue Tests

Fatigue tests were run in the same manner as for previously reported groups of stiffened panel samples. The criterion of failure was kept as the complete release of panel from stiffener at any single-spot weld. At high loads, this failure was a sudden pulling out of the weld button and caused sufficient drop in load to actuate the cut-off mechanism (which was sensitive to about 30 lb). At lower loads, the situation was more complicated. The total drop in load during the lifetime of a sample was usually less than 60 pounds and this drop was rather gradual. The cut-off mechanism would stop the machine but it was not always true that such stopping implied the complete failure of any weld. Consequently a frequent inspection was needed despite the improved cut-off arrangement.

At low loads, several visible phenomena preceded failure. There were often longitudinal cracks (i.e., cracks through welds along a line of spots) which became severe enough to free the panel from the stiffener on one side of the crack. Such cracks often occurred a long time before final failure and were not observed to correlate in any way with final failure. At a later time in the life of any one sample, there might appear horizontal cracks extending in a direction perpendicular to the axis of loading. Such cracks seemed to have their origin in the heat cracks originally in the weld. In general, these cracks had little correlation with position or time of occurrence of final failure.

The fatigue data are given in tables 17 and 18, and load-life curves plotted from these data are shown in figures 32 and 33.

## Examination of Failure.

The actual failure of the welds took place in much the same manner as happened for sound welds in stiffened-panel samples. Failure started at the inner alclad protrusion and a crack propagated either into the weld slug parallel to the faying surface, directly outward toward the external alclad, or around the weld button in the affected area. The type of failure seemed to depend upon the types of stress acting on the particular weld; generally, more than one type of cracking was present. Various examples are illustrated in figures 28 to 31.

For these overheated welds, especially in the heavier gage stock, failure appeared rather frequently in the sheet material. These cracks generally appeared next to the weld in the 0.032-inch stock (see fig. 28 (c,d)) and appeared running through the weld center in a curving pattern in the 0.040-inch stock. (See fig. 30.)

There was no evidence of sample failure caused by transverse welding cracks for the 0.25-inch or for the 0.32-inch sheet. However, in the 0.040-inch panels, cracks appeared through the weld (see fig. 30) with each button separating through the welding cracks. These cases represent severe overheating with resulting widespread cracking to each surface as well as excessive weld penetration (even to the external alclad). In most cases, welding cracks appeared to be extended by cyclic loading but only for the severely overheated spots in 0.040-inch sheet did such cracks appear to cause final spot failure.

With many or large welding cracks, considerable disruption of the weld structure occurred under the action of the fatigue stresses. The action seemed to be one of wearing away, by vibration of adjacent areas, considerable portions of weld material around the cracks. This is shown in figures 28 and 29.

In general, transverse welding cracks in individual spots did not seem to affect drastically the strength - either static or fatigue. The damage caused within badly cracked welds may, however, have other detrimental effects since it would open the center of the weld to the atmosphere.

## Discussion of Results and Conclusions

Stiffened panels of 0.032-inch stock seem to afford the best analysis of the effect of welding cracks on fatigue strengths since, for this thickness, the cracked welds were of the same dimensions as sound welds in samples previously tested. Figure 35 shows fatigue curves for sound-weld samples of 0.032-inch panels (taken from reference 1, figs. 20 and 21) and for cracked-weld samples of 0.032-inch panels (taken from figs. 32 and 33) of this report. It is clear that, for these tests, cracked welds have higher fatigue strengths than sound welds. Similar comparisons for the other sheet thicknesses tested show that the cracked-weld samples are, in general, stronger than sound-weld samples. Samples of 0.040-inch stock do not show so great an increase in strength as might be expected to correspond to the large size of the cracked welds. (See fig. 36.) It seems probable that, in this case, the excessive heat cracking was harmful. Curves for samples of 0.025-inch stock are shown in figure 34. Here the small difference between curves for sound and for cracked-weld samples is compatible with the relatively small amount of cracking observed. It should also be remembered that welds in this 0.025-inch stock varied greatly in dimension.

Figure 37 shows strength (total load divided by total cross section of stiffener plus panel) plotted against sheet thickness. As in the similar graph (reference 1, fig. 22) for sound weld samples, the fatigue strength for constant life seems to be following the buckling stress rather than the crippling stress. The greater curvature of the cracked-weld fatigue-strength curves may be attributed to the variation in weld quality in the 0.025- and the 0.040-inch panels.

In summary, the following conclusions may be drawn from comparison of the present tests on cracked-weld samples with previous tests on sound-weld samples:

1. Transverse cracks from overheating did not, in general, incept fatigue cracks leading to failure.

2. In general, the cracked-weld samples were stronger in both static and fatigue tests than corresponding sound-weld samples.

Battelle Memorial Institute,
Columbus, Ohio, June 1, 1943.

## REFERENCE

1. Russell, H. W., Jackson, L. R., Grover, H. J., and Beaver, W. W.: Fatigue Characteristics of Spot-Welded 24S-T Aluminum Alloy. NACA A.R.R. No. 3F16, June 1943.

TABLE 1

SPOT-WELDING CONDITIONS FOR 0.040-INCH LAP-JOINT SAMPLES WITH 3/8-INCH WELD SPACING

1. Data furnished by the Rensselaer Polytechnic Institute
2. Surface treatment:

   Paint removal and degreasing: Navy Spec. C-67-C

   Removing oxide: R.P.I. solution 10
3. Spot welding:

Secondary Current

| Peak value (amps.) | Time in milliseconds* To peak | Total | Electrode Tips Upper | Lower |
|---|---|---|---|---|
| 26,000 | 16.4 | 73.0 | 4 in. rad dome | 4 in. rad dome |

Electrode Pressure

| Welding pressure (lb) | Maximum value (lb) | Time from peak current in milliseconds To start | To max. |
|---|---|---|---|
| 600 | 1800 | 16.7 | 28.8 |

*Total time from start of welding current until decay to 10 percent of peak value.

TABLE 2.—STATIC TESTS ON 0.040-INCH LAP-JOINT SAMPLES WITH 3/8-INCH SPOT SPACING

| Sample | Tested by | Total load (lb) | Load (lb/in. of joint) | Load (lb/spot) |
|---|---|---|---|---|
| Single spot Test coupon | R.P.I. | 432 | --- | 432 |
| 1A5 (11) | Battelle | 3340 | 668 | 304 |
| 1A3 (11) | ---do--- | 3480 | 696 | 316 |

TABLE 3.- DIMENSIONS AND PROPERTIES OF SPOT WELDS (0.040-in. sheet - 3/8-in. weld spacing made at R.P.I.)

| Dimensions | | Hardness (Vickers) | |
|---|---|---|---|
| Diameter, inch . . . . | 0.160 | 24S-T sheet . . . . . | 132 |
| Penetration, percent . . | 55 | Area around weld. . . | 120 |
| Indentation, inch. . . | 0.004 | Dendritic region. . . | 112 |
| Maximum offset, inch . | 0.010 | Center of weld. . . . | 105 |
| Maximum width of dendritic zone, inch . | 0.010 | | |

Note: Hardness values within any one area held very constant except when porosity or incipient cracking was present in center zone with consequent low hardness.

TABLE 4. FATIGUE DATA FOR LAP JOINT SAMPLES OF 0.040" ALCLAD 24S-T WITH 11 SPOT WELDS SPACED 3/8" APART

| Sample Number | Maximum Load | | | Cycles to Failure | Type of Break |
|---|---|---|---|---|---|
| | Total lbs. | Lbs./in. of Joint | Lbs. per Spot | | |
| Ratio .25 | | | | | |
| 1A22(11) | 2200 | 440 | 200 | 18,600 | Pulled buttons. |
| 1A30(11) | 2100 | 420 | 191 | 26,300 | |
| 1A29(11) | 1570 | 314 | 143 | 77,400 | Fatigue cracks. |
| 1A28(11) | 1155 | 231 | 105 | 475,400 | |
| 1A19(11) | 1122 | 224 | 102 | 387,800 | |
| 1A25(11) | 890 | 178 | 81 | 1,902,600 | Fatigue cracks. |
| 1A21(11) | 840 | 168 | 76.5 | 2,610,000 | " " |
| 1A10(11) | 820 | 164 | 74.5 | 1,497,400 | " " |
| 1A9(11) | 792 | 158 | 72 | >9,903,600 | " " |
| Reload | 1735 | 347 | 191 | 25,000 | |
| Ratio .50 | | | | | |
| 1A13(11) | 2820 | 564 | 257 | 4,600 | Shear. |
| 1A24(11) | 2360 | 472 | 214 | 4,100 | " |
| 1A12(11) | 2060 | 412 | 187 | 90,200 | Fatigue cracks. |
| 1A27(11) | 1770 | 354 | 161 | 163,500 | " " |
| 1A14(11) | 1530 | 306 | 139 | 262,100 | " " |
| 1A26(11) | 1300 | 260 | 118 | 521,200 | " " |
| 1A23(11) | 1120 | 224 | 102 | 703,800 | " " |
| 1A20(11) | 946 | 189 | 86 | 2,807,500 | " " |
| 1A17(11) | 990 | 198 | 90 | 1,284,100 | " " |
| Ratio .75 | | | | | |
| 1A15(11) | 2840 | 568 | 258 | 181,700 | Fatigue cracks. |
| 1A8(11) | 2730 | 546 | 248 | 217,200 | " " |
| 1A11(11) | 2820 | 564 | 257 | 179,100 | " " |
| 1A7(11) | 2310 | 462 | 210 | 582,400 | " " |
| 1A1(11) | 2180 | 436 | 198 | 564,700 | " " |
| 1A4(11) | 2002 | 400 | 182 | 882,300 | " " |
| 1A16(11) | 1570 | 314 | 143 | 1,880,200 | " " |
| 1A2(11) | 1365 | 273 | 124 | >9,576,000 | Did not fail. |
| Reload | 2100 | 420 | 191 | 327,800 | Fatigue cracks. |
| 1A6(11) | 1410 | 282 | 128 | 3,485,100 | " " |

TABLE 5. SURFACE PREPARATION AND WELDING CONDITIONS FOR LAP JOINT SAMPLES

(a) Samples from Company A

| Surface Treatment | Solution | Time | Temp. | Welding Set-up | D.C. | Machine Data | | Electrodes | Test Sample Strength Spot | Spacing |
|---|---|---|---|---|---|---|---|---|---|---|
| Cleaner | Diversey | 5 min. | 212°F | Precomp. Press | 60 | Make- | Sciaky | (Mallory #3) | $1\frac{1}{4}$" | 3/4" |
| Rinse | Water | 1 min. | 40°F | Weld. Press | 60 | Model- | PMCO2S | Upper: $\frac{1}{2}$" 2" radius | | |
| Etch | Diversey | 6 min. | 180°F | Recomp. Press | 60 | Number- | 1135(14) | | 470#/spot | 460#/spot |
| Rinse | Water | 1 min. | 40°F | D.C. Volts | 110 | Throat size- | 33" | Lower: $\frac{1}{2}$" 6" radius | | |
| Dry | Comp. Air | | | D.C. Amps. | 220 | | | | | |

Coolant water temperature 40°F. Flow rate- 3 gal. per minute.

**********************

(b) Samples from Company B

| Thickness | Etching Time in 4% HF Sol. | Weld | Forge | Current | Switch | Pre-comp. | DBC | Re-comp. | Appl. | Blks. | Electrodes Upper | Electrodes Lower |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.025 | 25 sec. | 40 | 40 | 175 | 34 | Yes | 8 | 8 | Vari. | 5 | $\frac{1}{2}$" face 3" R | 7/8" face 10" R |
| 0.040 | 45 sec. | 50 | 50 | 240 | 44 | Yes | 10 | 10 | Vari. | 5 | $\frac{1}{2}$" face 3" R | 7/8" face 10" R |

Used Research Sciaky Machine.

TABLE 6. STRUCTURAL DETAILS OF SPOT WELDS FROM VARIOUS COMPANIES

| Manufacturer | Description of Sample | Static Breaking Load in Lbs./ Spot | Button Dia. Inches | Max. Pen. of Spot % | Maximum Indentation Inches | Max. Offset Inches | Remarks |
|---|---|---|---|---|---|---|---|
| R. P. I. | 0.040" - $1\frac{1}{4}$" spacing | 605 ± 5 | 0.220 | 50 | 0.002 | 0.002 | |
| R. P. I. | 0.040" - 3/4" spacing | 595 ± 5 | 0.215 | 50 | 0.002 | 0.002 | |
| R. P. I. | 0.025" - $1\frac{1}{4}$" spacing | 335 ± 2 | 0.145-0.150 | 44 | neg. | neg. | |
| R. P. I. | 0.025" - 3/4" spacing | 312 ± 5 | 0.140-0.150 | 38 | neg. | neg. | |
| Company B | 0.025" - 3/4" spacing | 326 ± 5 | 0.145-0.155 | 40-60 | 0.003 | 0.005 | Peanut shaped. |
| Company B | 0.040" - 3/4" spacing | 615 ± 1 | 0.220-0.240 | 60-70 | 0.005 | 0.004 | Peanut shaped. |
| Company A | 0.040" - 3/4" spacing | 479 ± 10 | 0.180-0.190 | 75-80 | 0.008 | 0.008 | Some transverse cracking. |
| Company A | 0.040" - $1\frac{1}{4}$" spacing | 522 ± 10 | 0.190-0.200 | 65-70 | 0.004 | 0.005 | |

TABLE 7. FATIGUE DATA ON LAP JOINT SAMPLES SPOT WELDED BY COMPANY A
0.040" ALCLAD 24S-T WITH 4 SPOT WELDS SPACED 1-1/4" APART

| Sample Number | Maximum Load | | | Cycles to Failure | Type of Break |
|---|---|---|---|---|---|
| | Total lbs. | Lbs./in. of Joint | Lbs. per Spot | | |
| Ratio .25 | | | | | |
| A-4(4) | 1144 | 229 | 286 | 23,400 | Pulled button and fatigue cracks. |
| A-12(4) | 916 | 183 | 229 | 52,900 | Shear all welds. |
| A-6(4) | 800 | 160 | 200 | 331,000 | Fatigue cracks. |
| A-5(4) | 668 | 133 | 167 | 622,700 | |
| A-13(4) | 532 | 106 | 133 | 699,700 | Fatigue cracks. |
| A-15(4) | 456 | 91 | 114 | 2,555,500 | " " |
| Ratio .50 | | | | | |
| A-14(4) | 1712 | 343 | 428 | 4,500 | Shear |
| A-9(4) | 1144 | 229 | 286 | 276,000 | Fatigue cracks. |
| A-10(4) | 764 | 152 | 191 | 1,768,400 | |
| Ratio .75 | | | | | |
| A-8(4) | 1528 | 305 | 382 | 274,400 | Fatigue cracks. |
| A-7(4) | 1144 | 229 | 286 | 1,124,900 | " " |
| A-11(4) | 856 | 171 | 214 | 6,343,500 | " " |

TABLE 8. FATIGUE DATA ON LAP JOINT SAMPLES SPOT WELDED BY COMPANY A
0.040" ALCLAD 24S-T WITH 6 SPOT WELDS SPACED 3/4" APART

| Sample Number | Maximum Load | | | Cycles to Failure | Type of Break |
|---|---|---|---|---|---|
| | Total lbs. | Lbs./in. of Joint | Lbs. per Spot | | |
| Ratio .25 | | | | | |
| A-13(6) | 1716 | 343 | 286 | 6,100 | Shear |
| A-14(6) | 1488 | 298 | 248 | 28,400 | " |
| A-5(6) | 1260 | 252 | 210 | 86,200 | Fatigue cracks. |
| A-4(6) | 1002 | 200 | 167 | 229,900 | " " |
| A-6(6) | 744 | 149 | 124 | 771,100 | Fatigue cracks. |
| A-7(6) | 573 | 114 | 95.5 | 1,554,700 | " " |
| A-8(6) | 579 | 116 | 96.5 | 1,592,500 | " " |
| A-9(6) | 546 | 109 | 91 | 2,785,700 | " " |
| A-15(6) | 513 | 102 | 85.5 | 2,842,400 | " " |
| Ratio .75 | | | | | |
| A-11(6) | 2568 | 513 | 428 | 19,300 | Shear |
| A-12(6) | 1716 | 343 | 286 | 710,000 | Pullet button and fatigue cracks. |
| A-10(6) | 1440 | 288 | 240 | 1,250,000 | Fatigue cracks. |

TABLE 9. FATIGUE DATA ON LAP JOINT SAMPLES, SPOT WELDED BY COMPANY B
0.025" ALCLAD 24S-T WITH 6 SPOT WELDS SPACED 3/4" APART

| Sample Number | Maximum Load Total lbs. | Maximum Load Lbs./in. of Joint | Maximum Load Lbs./Spot | Cycles to Failure | Type of Break |
|---|---|---|---|---|---|
| Ratio .25 | | | | | |
| B1-4(6) | 858 | 171 | 143 | 4,100 | Shear |
| B1-8(6) | 744 | 149 | 124 | 119,300 | Fatigue cracks. |
| B1-6(6) | 684 | 139 | 114 | 207,800 | " " |
| B1-5(6) | 570 | 114 | 95 | 178,900 | " " |
| B1-10(6) | 552 | 110 | 92 | 584,600 | " " |
| B1-15(6) | 480 | 96 | 80 | 798,400 | " " |
| B1-16(6) | 417 | 83 | 69.5 | 1,003,100 | Pulled buttons & shear. |
| B1-17(6) | 384 | 77 | 64 | 1,883,400 | |
| B1-18(6) | 348 | 70 | 58 | 2,085,800 | Fatigue cracks. |
| Ratio .50 | | | | | |
| B1-13(6) | 960 | 192 | 160 | 81,600 | Fatigue cracks. |
| BI-11(6) | 684 | 137 | 114 | 595,300 | " " |
| B1-12(6) | 543 | 108 | 90.5 | 1,668,100 | " " |
| Ratio .75 | | | | | |
| B1-14(6) | 960 | 192 | 160 | 156,600 | Fatigue cracks. |

TABLE 10. FATIGUE DATA ON LAP JOINT SAMPLES SPOT WELDED BY COMPANY B
0.040" ALCLAD 24S-T WITH 6 SPOTWELDS SPACED 3/4" APART

| Sample Number | Maximum Load Total lbs. | Maximum Load Lbs./in. of Joint | Maximum Load Lbs./Spot | Cycles to Failure | Type of Break |
|---|---|---|---|---|---|
| Ratio .25 | | | | | |
| B-1(6) | 1926 | 385 | 321 | 11,500 | |
| B-2(6) | 1764 | 353 | 294 | 18,400 | |
| B-3(6) | 1440 | 288 | 240 | 62,800 | |
| B-4(6) | 1218 | 244 | 203 | 158,700 | |
| B-13(6) | 1056 | 211 | 176 | 265,400 | |
| B-5(6) | 900 | 180 | 150 | 438,600 | Fatigue cracks. |
| B-6(6) | 768 | 154 | 128 | 834,500 | " " |
| B-7(6) | 642 | 128 | 107 | 1,901,600 | |
| B-11(6) | 516 | 103 | 86 | >10,103,100 | |
| Reload | 918 | 183 | 153 | 770,700 | Fatigue cracks. |
| B-10(6) | 546 | 109 | 91 | >10,775,200 | Did not fail. |
| Ratio .75 | | | | | |
| B-15(6) | 2562 | 512 | 427 | 97,900 | Pulled buttons. |
| B-9(6) | 1920 | 384 | 320 | 571,400 | Fatigue cracks. |
| B-12(6) | 1446 | 289 | 241 | 2.543,200 | " " |

TABLE 11.—STATIC TESTS ON STITCHED SAMPLES

| Sample type and number | Breaking load (lb) | Breaking load (lb/in.) | Breaking load (lb/staple) | Specified load (lb/staple) |
|---|---|---|---|---|
| A-2 | 3800 | 760 | 475 | 480 |
| B-2 | 1950 | 390 | 487 | 480 |
| C-1 | 4360 | 872 | 484 | |
| D-1 | 2250 | 450 | 140 | |
| E-1 | 1920 | 384 | 480 | 560 |
| F-1 | 2000 | 400 | 500 | 560 |
| G-2 | 3900 | 780 | 487 | 560 |
| H-1 | 5850 | 1170 | 487 | 560 |

TABLE 13.- WELDING CONDITIONS FOR STIFFENED PANEL SAMPLES

WITH 2-INCH SPOT-WELD SPACING

| Gage (in.) | Secondary Current: Peak value (amps.) | Secondary Current: Time in milliseconds: To peak | Secondary Current: Time in milliseconds: Total | Electrode Tips: Upper | Electrode Tips: Lower |
|---|---|---|---|---|---|
| 0.032 inch sr<br>0.032 inch pl | 26,000 | 16.4 | 73.0 | $2\frac{1}{2}$ inch dome | 5/16 inch X10° Flat |

| Welding pressure (lb) | Electrode Pressure: Forging Pressure: Maximum value (lb) | Electrode Pressure: Forging Pressure: Time from peak curent in milliseconds: To start | Electrode Pressure: Forging Pressure: Time from peak curent in milliseconds: To maximum | Surface Treatment: Paint removing and degreasing | Surface Treatment: Removing oxide |
|---|---|---|---|---|---|
| 600 | 1800 | 16.7 | 28.8 | Navy Spec. C-67-C | R.P.I. solution 10 |

| Shear Strength Single Spot Specimen (lb) | Remarks |
|---|---|
| 432 | 5 cracked welds. Others sound. |

TABLE 12. FATIGUE DATA ON LAP JOINT SAMPLES OF 0.040" ALCLAD 24S-T JOINTED BY STEEL WIRE STAPLES

| Sample Number | Maximum Load* Total lbs. | Lbs./In. | Lbs./Staple | Cycles to Failure | Type of Failure |
|---|---|---|---|---|---|
| A-1 | 3200 | 640 | 400 | 3,600 | Sheared staples. |
| A-3 | 2140 | 428 | 268 | 61,600 | " " |
| A-4 | 1600 | 320 | 200 | 210,700 | Sheared & pulled staples. |
| B-1 | 1020 | 210 | 255 | 70,500 | Sheared staples. |
| B-3 | 855 | 171 | 214 | 352,600 | " " |
| B-4 | 750 | 150 | 188 | 1,408,900 | " " |
| C-2 | 3200 | 640 | 356 | 21,300 | Cracked across sheet. |
| C-3 | 2140 | 428 | 237 | 174,600 | " " " |
| C-4 | 1870 | 374 | 207 | 383,600 | " " " |
| D-3** | 1280 | 256 | 80 | 8,600 | Sheared & pulled staples. |
| D-4 | 855 | 171 | 53 | 28,100 | Pulled staples. |
| E-2 | 1070 | 214 | 268 | 93,700 | Cracked to edge of lap. |
| E-3 | 964 | 192 | 241 | 102,200 | " " " " " |
| E-4 | 856 | 171 | 214 | 309,800 | " " " " " |
| F-5 | 1500 | 300 | 375 | 18,200 | Sheared staples. |
| F-3 | 1280 | 256 | 320 | 62,800 | " " |
| F-2 | 1070 | 214 | 268 | 226,000 | " " |
| F-4 | 910 | 182 | 228 | 349,600 | " " |
| F-6 | 770 | 154 | 193 | 987,100 | Cracked across sheet. |
| G-1 | 3200 | 640 | 400 | 6,400 | Cracked across sheet. |
| G-3 | 2038 | 407 | 255 | 60,200 | " " " |
| G-4 | 1600 | 320 | 200 | 313,800 | " " " |
| H-2 | 3840 | 768 | 320 | 14,925 | Cracked in sheet. |
| H-3 | 2680 | 536 | 223 | 54,700 | " " " |
| H-4 | 2250 | 450 | 187 | 97,600 | " " " |

*All tests run at R=Min. load/max. load =0.25.

**Samples of Type D had zero over-lap.

TABLE 14. COMPRESSION FATIGUE RESULTS ON 0.032" ALCLAD 24S-T STIFFENED PANELS, SPOT WELDS SPACED 2" APART

Ratio $\frac{\text{min. stress}}{\text{max. stress}}$

| Sample | Max. Load (lbs.) | Cycles to Failure | Type of Break |
|---|---|---|---|
| **Ratio .25** | | | |
| 0-13 | 3400 | 5,500 | Weld pulled. |
| 0- 9 | 3000 | 9,900 | " " |
| 0-18 | 2400 | 81,300 | " " |
| 0- 2 | 2300 | 97,000 | " " |
| 0-15 | 2100 | 3,939,100 | Cracks through welds. |
| 0-20 | 2000 | 8,016,400 | " " " |
| **Ratio .50** | | | |
| 0-14 | 4000 | 4,800 | Weld pulled. |
| 0- 4 | 3400 | 12,900 | " " |
| 0-11 | 3000 | 618,000 | " " |
| 0-19 | 2800 | 169,300 | " " |
| 0- 8 | 2300 | 4,571,100 | " " |
| **Ratio .75** | | | |
| 0-1 | 6000 | 21,500 | Weld pulled. |
| 0-7 | 5600 | 362,600 | Two welds pulled. |
| 0-3 | 5000 | 1,802,800 | Weld pulled. |
| 0-6 | 4000 | 2,931,300 | " " |
| 0-12 | 3800 | 4,562,100 | Cracks on welds. |

TABLE 16. STATIC COMPRESSION TESTS ON STIFFENED PANELS (Overheated Spot Welds)

| Panel Thickness (Inches) | Weld Spacing (In.) | Area* A (Sq.In.) | 4 W (In.) | Area** A' (Sq.In.) | Average Buckling Load (Lbs.) | Average Buckling Stress P / A | Crippling Load $P_2$(Lbs.) | Crippling Stress $P_2/A$ | Crippling Stress $P_2/A'$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.025 | .75 | .275 | 1.436 | .198 | 1,650 | 6,000 | 8,650 | 31,500 | 43,700 |
| 0.025 | 1.25 | .275 | 1.436 | .198 | 1,700 | 6,200 | 8,175 | 29,800 | 41,300 |
| 0.032 | .75 | .306 | 1.84 | .221 | 3,000 | 9,800 | 9,000 | 29,500 | 40,700 |
| 0.032 | 1.25 | .306 | 1.84 | .221 | 2,850 | 9,300 | 8,550 | 28,000 | 38,700 |
| 0.040 | .75 | .342 | 2.30 | .254 | 3,300 | 9,650 | 9,650 | 28,200 | 38,000 |
| 0.040 | 1.25 | .342 | 2.30 | .254 | 4,000 | 11,700 | 8,600 | 25,300 | 34,000 |

* Total area of stiffener plus panel.

** Area of stiffener plus an effective area for the panel.

TABLE 15. WELDING CONDITIONS FOR STIFFENED PANEL SAMPLES WITH HEAT CRACKED WELDS

| Gage Inches[3] | Secondary Current[2] Peak Value Amps. | Secondary Current[2] Time in Millisec. To Peak | Secondary Current[2] Time in Millisec. Total[1] | Electrode Tips Upper | Electrode Tips Lower | Electrode Pressure Welding Pressure Lbs. | Electrode Pressure Max. Value Lbs. | Forging Pressure Time from Peak Current in Milliseconds To Start | Forging Pressure Time from Peak Current in Milliseconds To Max. | Surface Treatment Paint Removing & Degreasing. | Surface Treatment Removing Oxide | Shear Strength Single-Spot Specimen Lbs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .032"sr .040"pl | 37,800 | 15.9 | 59.1 | $2\frac{1}{2}$" Dome | 5/16"No° Flat | 800 | -- | -- | -- | Navy Spec C-67-C | R.P.I. Sol.#10 | 590 |
| | Remarks: One sound weld, others cracked. | | | | | | | | | | | |
| .032"sr .025"pl | 26,600 | 14.8 | 60.9 | $2\frac{1}{2}$" Dome | 5/16"No° Flat | 600 | -- | -- | -- | Navy Spec. C-67-C | R.P.I. Sol.#10 | 410 |
| | Remarks: 108 sound welds, others cracked. | | | | | | | | | | | |
| .032"sr .032"pl | 37,200 | 17 | 57 | $2\frac{1}{2}$" Dome | 5/16"No° Flat | 800 | -- | -- | -- | Navy Spec. C-67-C | R.P.I. Sol.#10 | 534 |
| | Remarks: All welds cracked. | | | | | | | | | | | |

[1]Total time from start of welding current until decay to 10% of peak value.
[2]Condenser discharge type of welder.

[3]Stringer = sr
Panel = pl

TABLE 17. COMPRESSION FATIGUE DATA ON ALCLAD 24S-T STIFFENED PANELS WITH CRACKED SPOT WELDS 3/4" APART

$$R = \frac{\text{min. stress}}{\text{max. stress}} = .25$$

| Sample | Maximum Load (lbs.) | Cycles to Failure |
|---|---|---|
| .040" panel | | |
| I-2 | 7200 | 91,700 |
| I-8 | 6000 | 691,100 |
| I-10 | 5000 | 3,311,000 |
| I-1 | 4800 | 1,825,700 |
| I-3 | 4600 | 5,105,900 |
| I-5 | 4000 | >10,040,300 |
| Reload | 6000 | 81,700 |
| .032" panel | | |
| E-6 | 7200 | 40,700 |
| E-2 | 6000 | 512,800 |
| E-4 | 5000 | 1,695,100 |
| E-8 | 4500 | 1,200,800 |
| E-10 | 4100 | 1,116,100 |
| E-5 | 3900 | 1,815,600 |
| E-1 | 3600 | 2,590,400 |
| E-3 | 3300 | >10,611,500 |
| .025" panel | | |
| M-8 | 6000 | 2,500 |
| M-4 | 5000 | 69,400 |
| M-9 | 4400 | 514,900 |
| M-7 | 4000 | 881,800 |
| M-10 | 3200 | 2,620,000 |
| M-1 | 3000 | 3,399,600 |
| M-3 | 2900 | 2,968,500 |
| M-2 | 2700 | >8,026,000 |

TABLE 18. COMPRESSION FATIGUE DATA ON ALCLAD 24S-T STIFFENED PANELS WITH CRACKED SPOT WELDS SPACED 1-1/4" APART

$$R = \frac{\text{min. stress}}{\text{max. stress}} = .25$$

| Sample | Max. Load (lbs.) | Cycles to Failure |
|---|---|---|
| .040" panel | | |
| J-7 | 7000 | 11,500 |
| J-1 | 6000 | 270,800 |
| J-5 | 5200 | 671,100 |
| J-9 | 4800 | 934,400 |
| J-4 | 4500 | 663,900 |
| J-10 | 4400 | 896,700 |
| J-3 | 3900 | 2,109,800 |
| J-2 | 3600 | 5,288,000 |
| .032" panel | | |
| F-2 | 6000 | 1,000 |
| F-9 | 5200 | 143,100 |
| F-3 | 4500 | 1,033,200 |
| F-10 | 4000 | 2,332,300 |
| F-1 | 3600 | 2,923,500 |
| F-8 | 3400 | > 10,622,000 |
| .025" panel | | |
| N-2 | 4500 | 4,100 |
| N-3 | 3800 | 3,600 |
| N-6 | 3000 | 40,300 |
| N-1 | 2600 | 428,800 |
| N-7 | 2500 | 26,400 |
| N-5 | 2000 | > 9,749,800 |
| Reload | 4000 | 3,000 |
| N-8 | 2300 | >10,053,800 |
| Reload | 3000 | 116,400 |

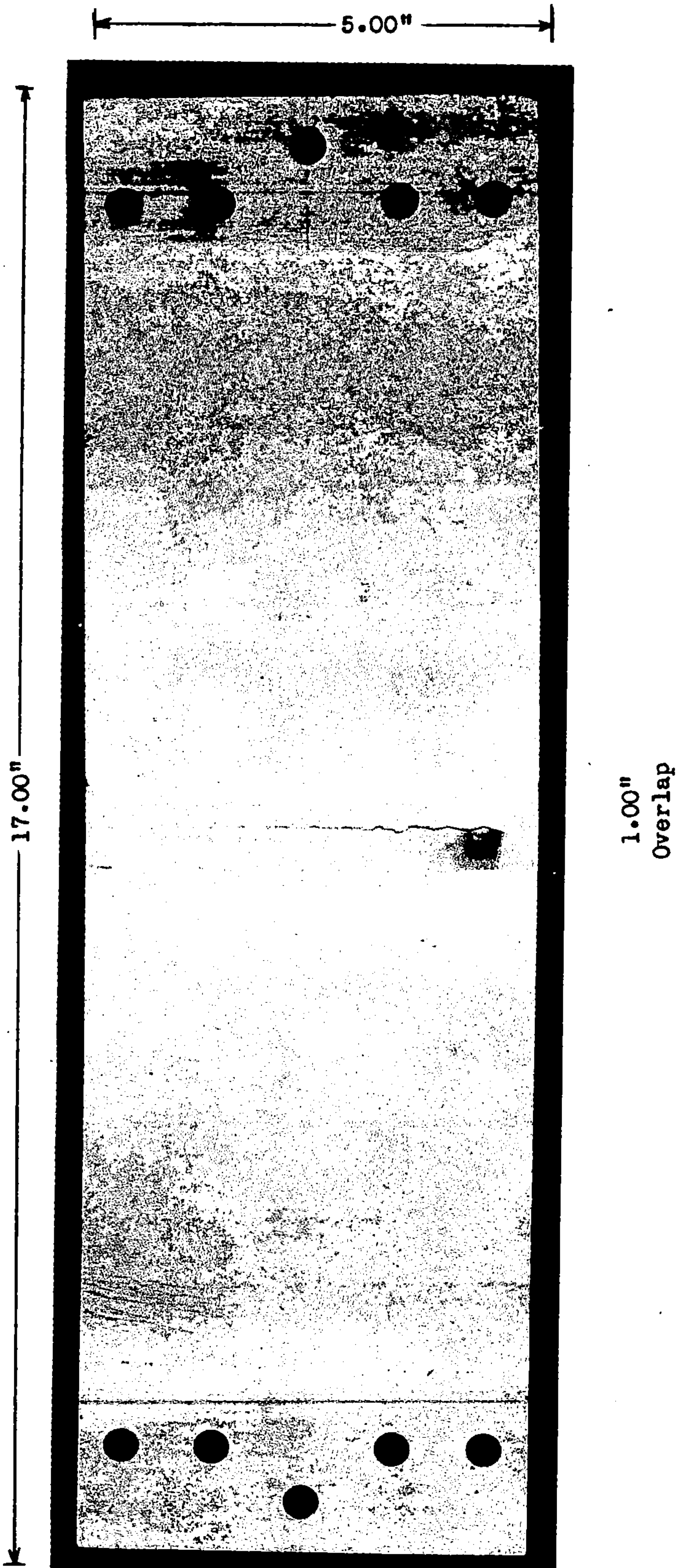
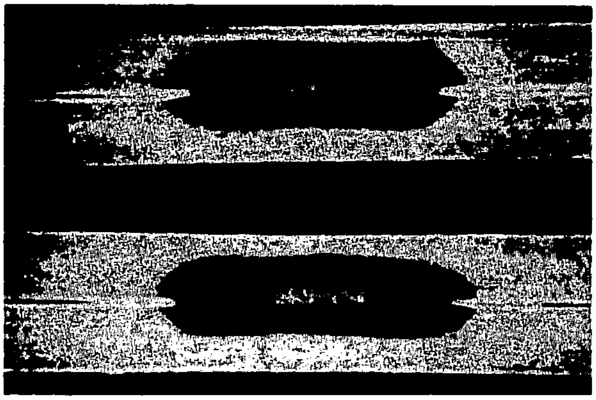
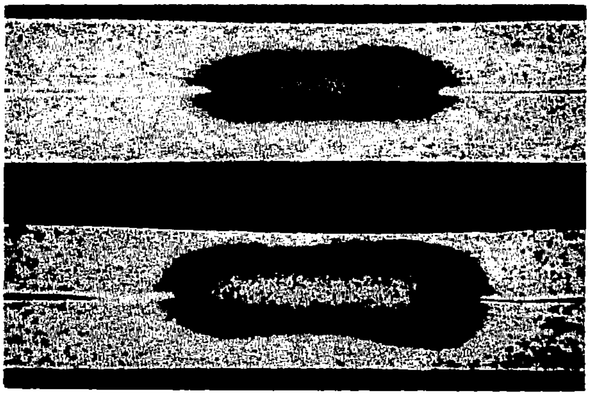



Figure 1. Typical Lap Joint Sample Tested in Tension Fatigue.
(Sample shown is of 0.040" Alclad 24S-T, and has 11 spot welds spaced 3/8" apart.
Note the failure by propagation of a fatigue crack along the line of welds.)



Keller's Etch 22084
10X

(a)
Typical welds.



Keller's Etch 22085
10X

(b)
Welds showing variation in size.

Figure 2.

R. P. I. Spot Welds from Untested Lap Joint Samples of 0.040" Alclad 24S-T with Spots Spaced 3/8" Apart.

**DIMENSIONS**

a – INDENTATION
b+c – PENETRATION
b–c = OFFSET
d – DIAMETER

**ZONES**

① EXTERNAL ALCLAD
② INTERNAL ALCLAD PROTRUSION INTO WELD ZONE
③ DENDRITIC REGION
④ CENTER ZONE
⑤ HEAT AFFECTED AREA
⑥ 24 S–T

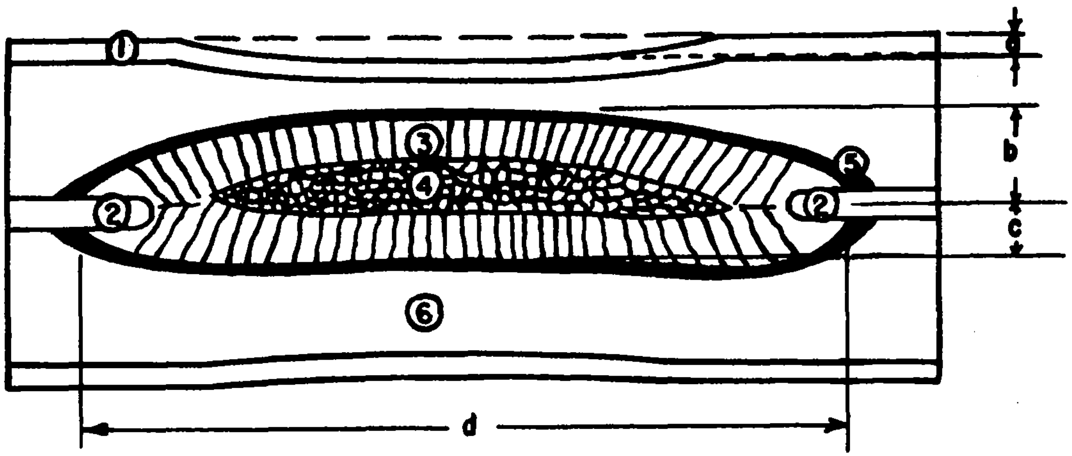



FIG. 3–SKETCH OF CROSS–SECTION OF SPOTWELD IN 24S–T ALCLAD SHOWING DIMENSIONS AND STRUCTURAL ZONES REFERRED TO IN TEXT.

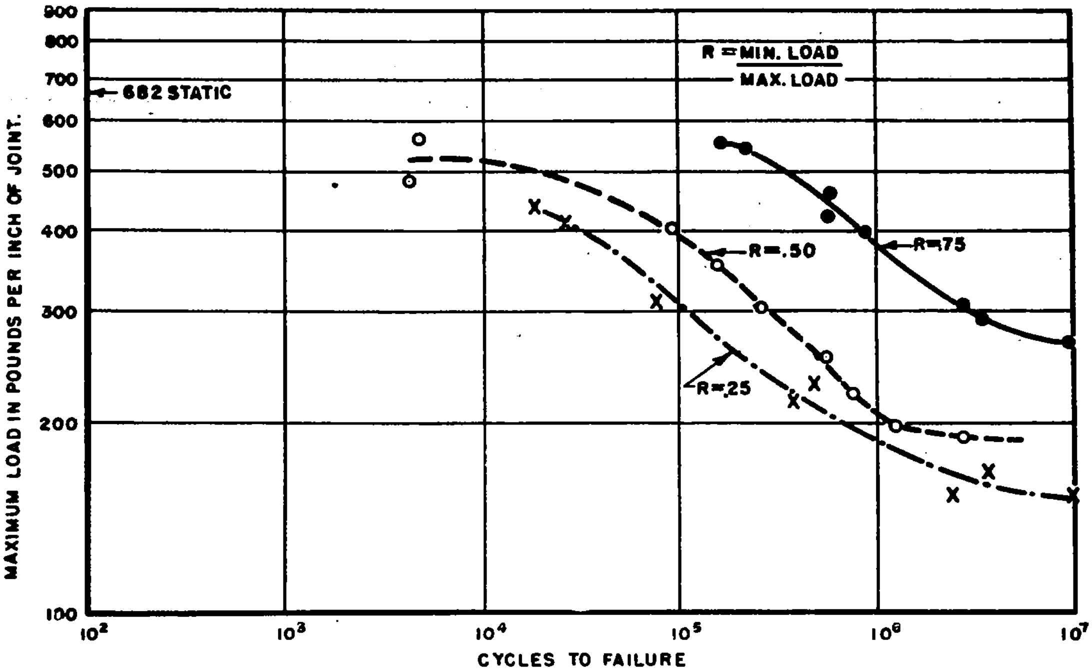



FIG. 4— FATIGUE CURVES FOR LAP JOINT SAMPLES OF 0.040" ALCLAD 24S-T, WITH 11 SPOTWELDS SPACED $\frac{3}{8}$" APART.

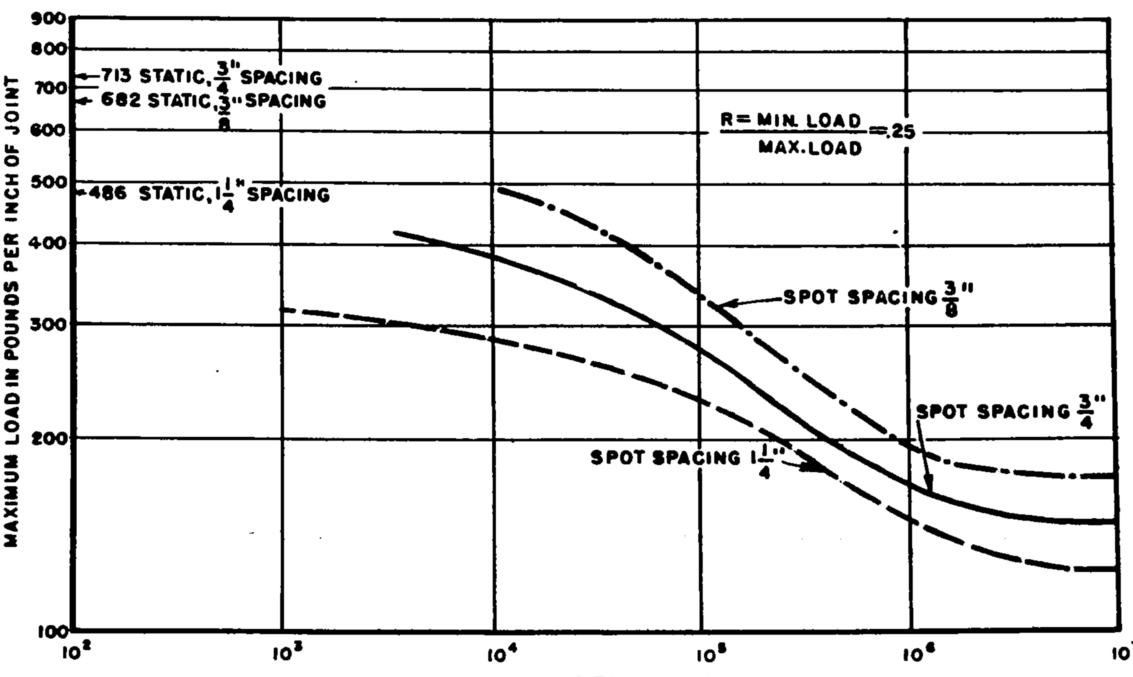
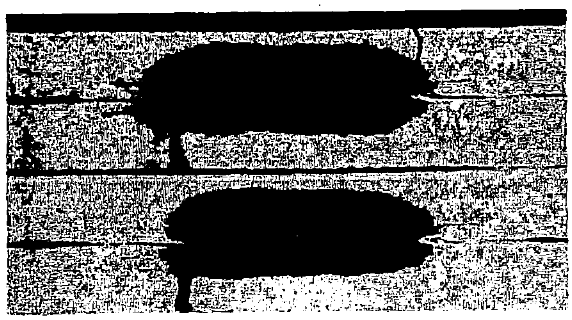


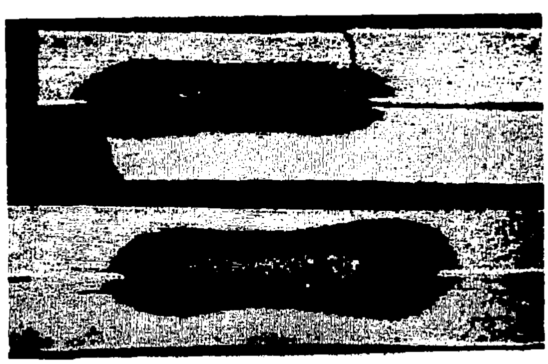

FIG. 6-FATIGUE CURVES FOR LAP JOINTS SAMPLES OF 0.040" ALCLAD 24S-T WITH VARIOUS SPOT SPACINGS.



Keller's Etch 10X

(a)

Welds Showing Typical Fatigue Cracks



Keller's Etch 10X

(b)

Two end welds from a failed sample. Note fatigue crack started in weld shown at top which did not reach weld at other end of row.

Figure 5.

Fatigue Failures in Spot Welds from Lap Joint Samples of 0.040" Alclad 24S-T with Spots Spaced 3/8" Apart.

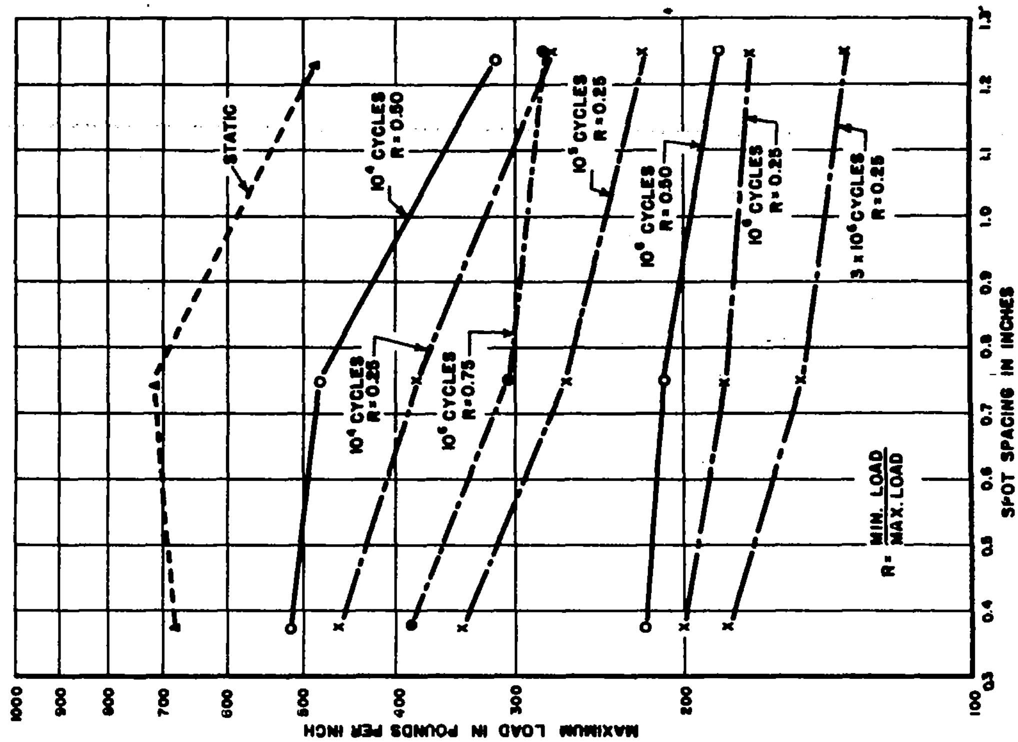



FIG. 7— VARIATION OF STRENGTHS OF SPOT WELDED LAP JOINT SAMPLES OF 0.040" ALCLAD 24 S-T WITH VARIATION IN SPOT SPACING.

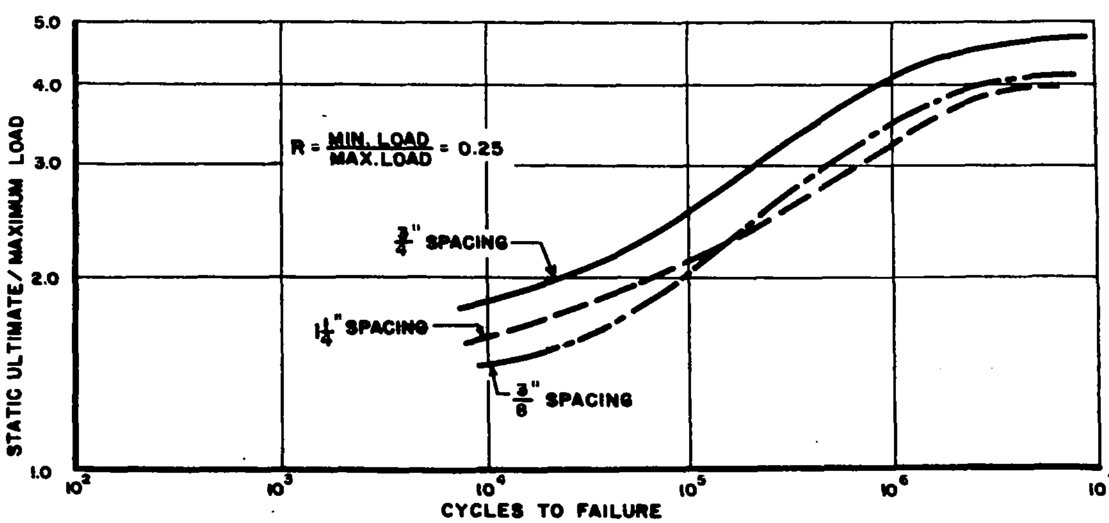
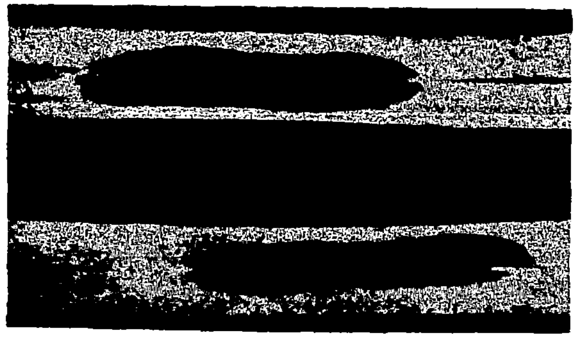



FIG. 8 — FATIGUE SENSITIVITY CURVES FOR LAP JOINT SAMPLES OF 0.040" ALCLAD 24 S —T



Keller's Etch 22089
10X

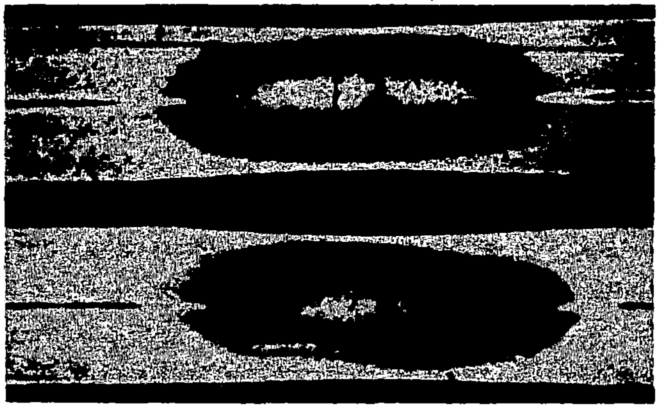
(a)
0.025" Sheet
3/4" Spot Spacing

Keller's Etch 22090
10X

(b)
0.040" Sheet
3/4" Spot Spacing

Figure 9.

Spot Welds from Company B (as received).

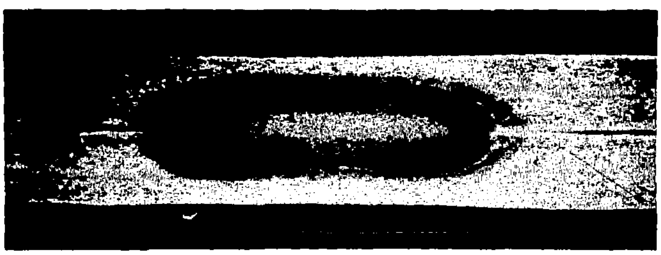


(a)

0.040" Sheet
3/4" Spot Spacing.

Keller's Etch

10X



(b)

0.040" Sheet
$1\frac{1}{4}$" Spot Spacing

Keller's Etch

10X

Figure 10.

Spot Welds from Company A (as received).

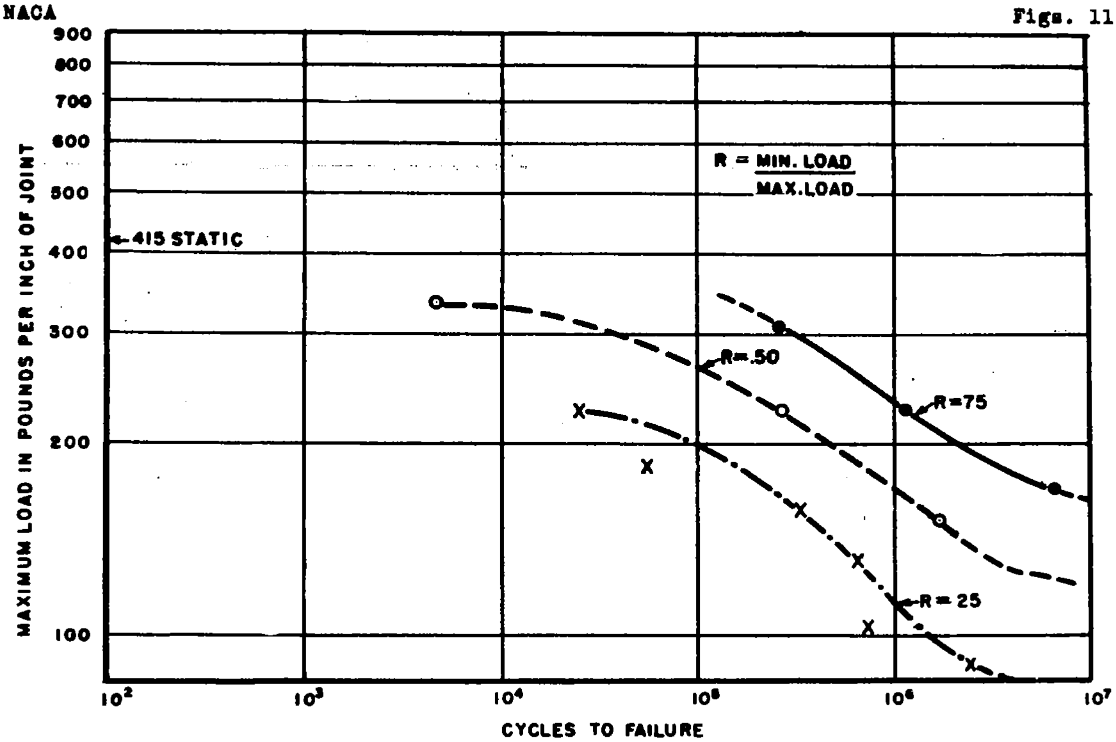



FIG. 11–FATIGUE CURVES FOR LAP JOINT SAMPLES SPOTWELDED BY COMPANY A, 0.040" ALCLAD 24S–T SHEET WITH 4 SPOTWELDS SPACED $1\frac{1}{4}$" APART

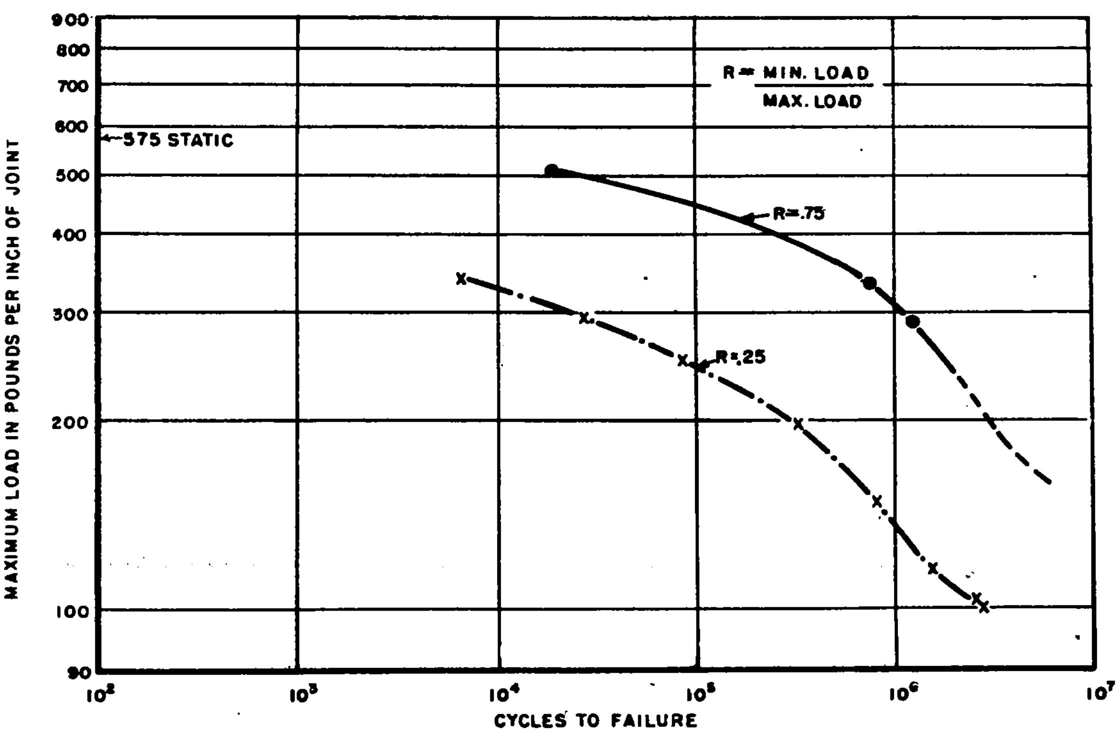



FIG. 12--FATIGUE CURVES FOR LAP JOINT SAMPLES SPOTWELDED BY COMPANY A 0.040 IN ALCLAD 24 S-T SHEET WITH 6 SPOTWELDS SPACED $\frac{3}{4}$" APART.

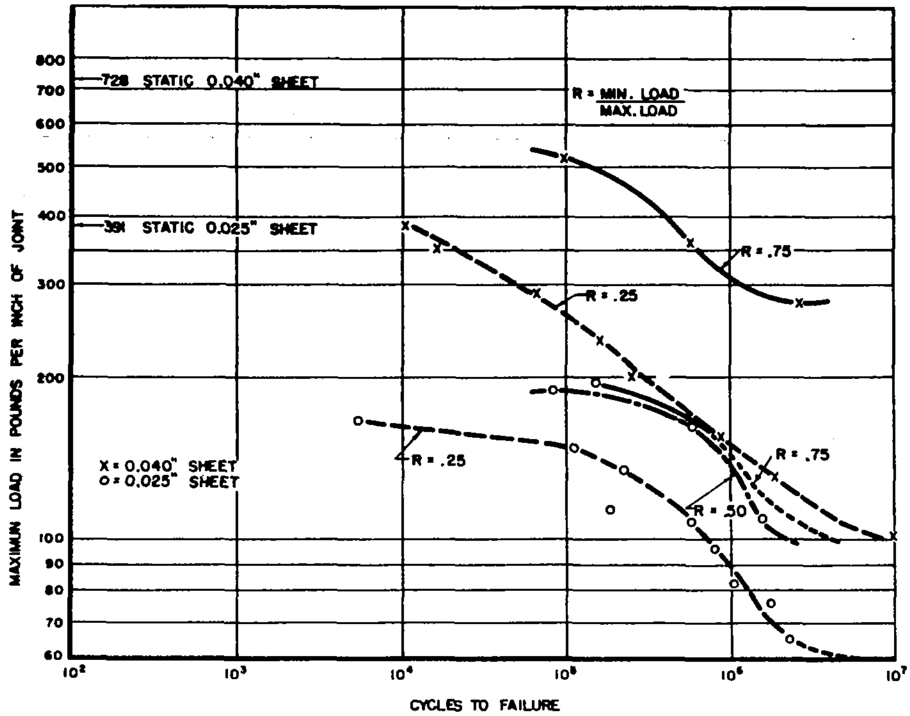



FIG. 13 – FATIGUE CURVES FOR LAP JOINT SAMPLES, SPOT WELDED BY COMPANY B, ALCLAD 24S-T SHEET WITH 6 SPOT WELDS SPACED 1/4 IN. APART.

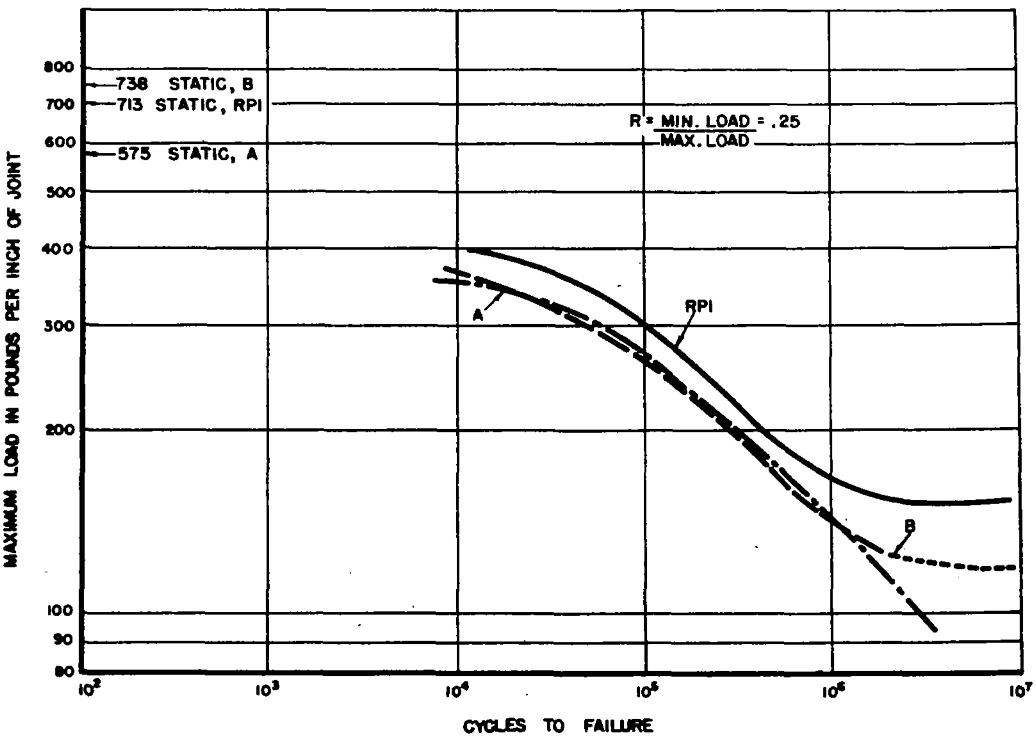
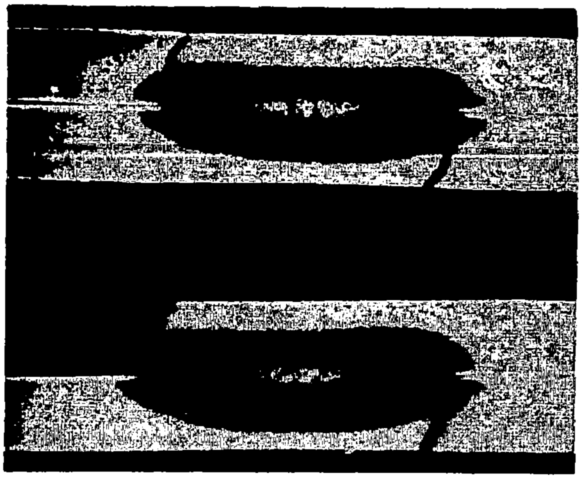
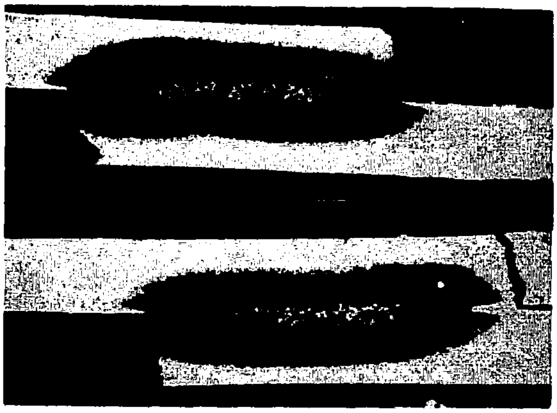



FIG. 17 – FATIGUE CURVES FOR LAP JOINT SAMPLES, SPOT WELDED BY DIFFERENT COMPANIES. 0.040" ALCLAD 24S-T WITH 6 SPOT WELDS SPACED 3/4" APART.



Keller's Etch 22092
10X

(a)
0.040" - 0.040" Sheet
3/4" Spot Spacing

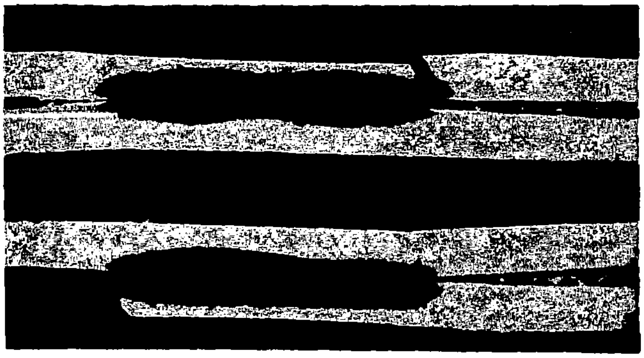


Keller's Etch 22093
10X

(b)
0.040" - 0.040" Sheet
$1\frac{1}{4}$" Spot Spacing

Figure 14.

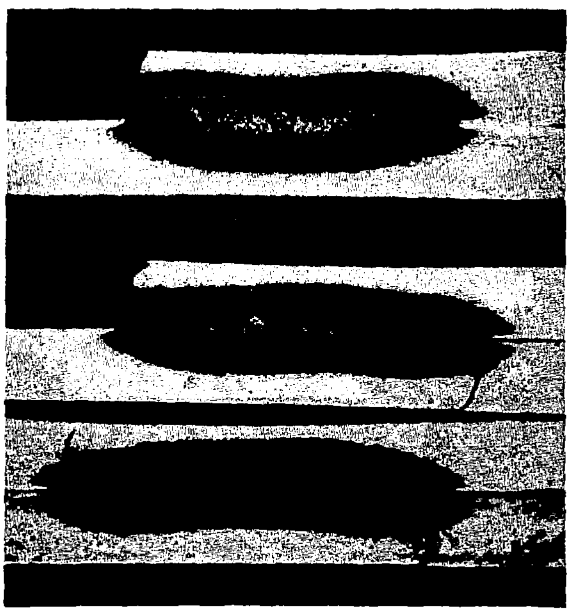
Fatigue Failures in Welds from Company A.



(a)

0.025" - 0.025" Sheet
Spot Spacing 3/4"

Keller's Etch 22094
10X



22095

(b)

0.040" - 0.040" Sheet
Spot Spacing 3/4"

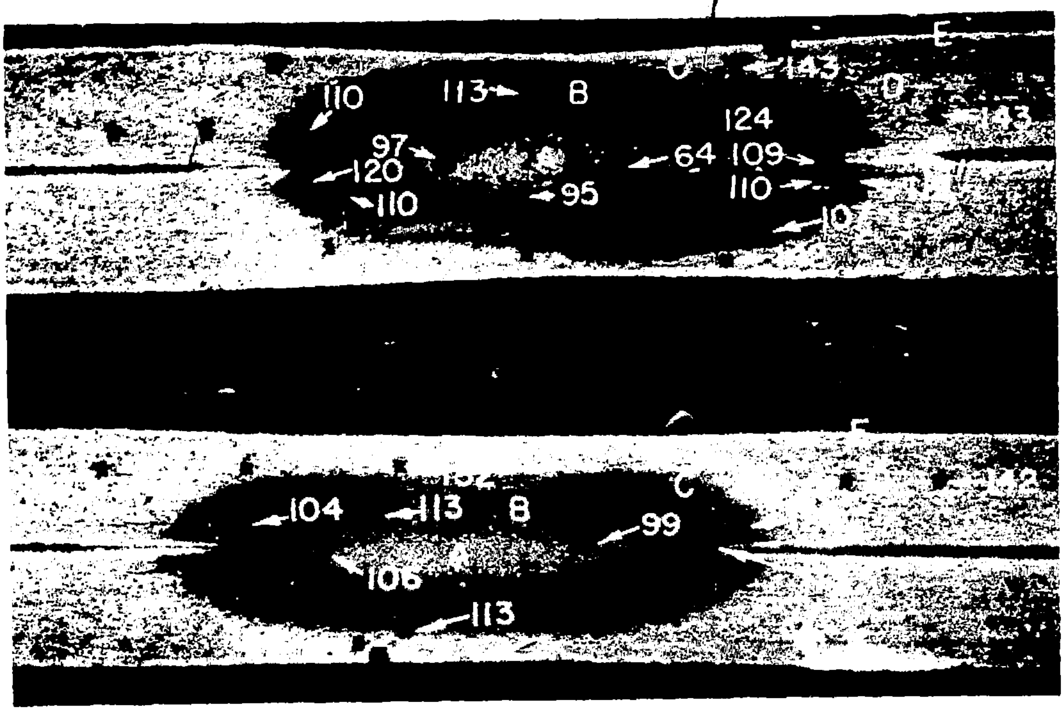
22096

Keller's Etch
10X

Figure 15.

Fatigue Failures in Welds from Company B.

64(low reading caused
by porosity)




15X

Keller's

Figure 16.

Vickers Hardness Measurements On 24S-T Aluminum Spot Welds

A- Equiaxed Center Region
B- Dendrites
C- Heat Affected Area
D- 24S-T
E- External Alclad
F- Internal Alclad

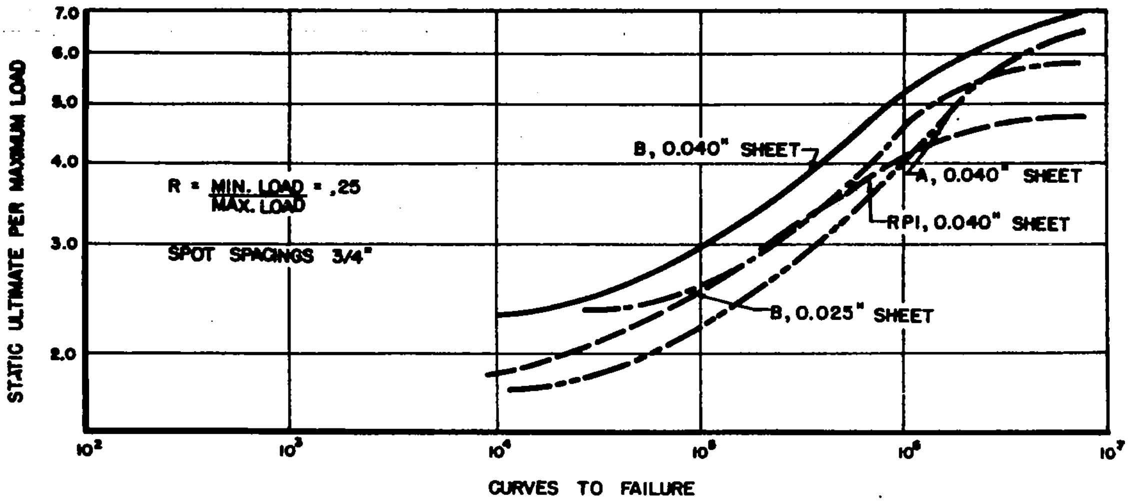



FIG. 18—FATIGUE SENSITIVITY CURVES FOR LAP JOINT SAMPLES SPOT WELDED BY DIFFERENT COMPANIES.

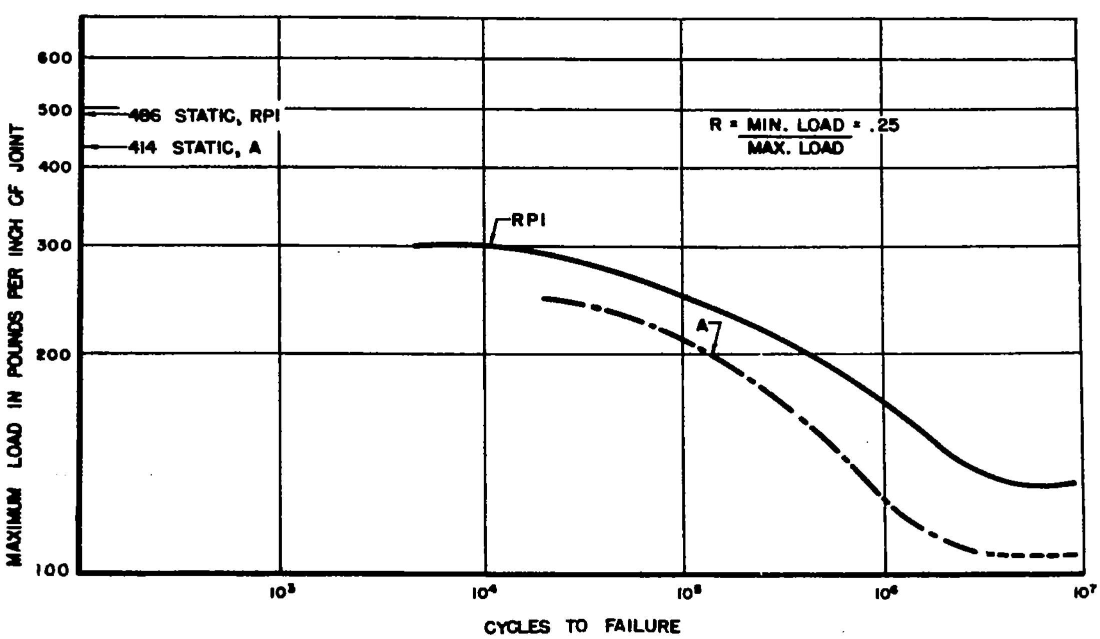



FIG. 19 FATIGUE CURVES FOR LAP JOINT SAMPLES SPOT WELDED BY COMPANY A AND SAMPLES SPOT WELDED BY RPI, 0.040" SHEET, 1 1/4" SPOT SPACING.

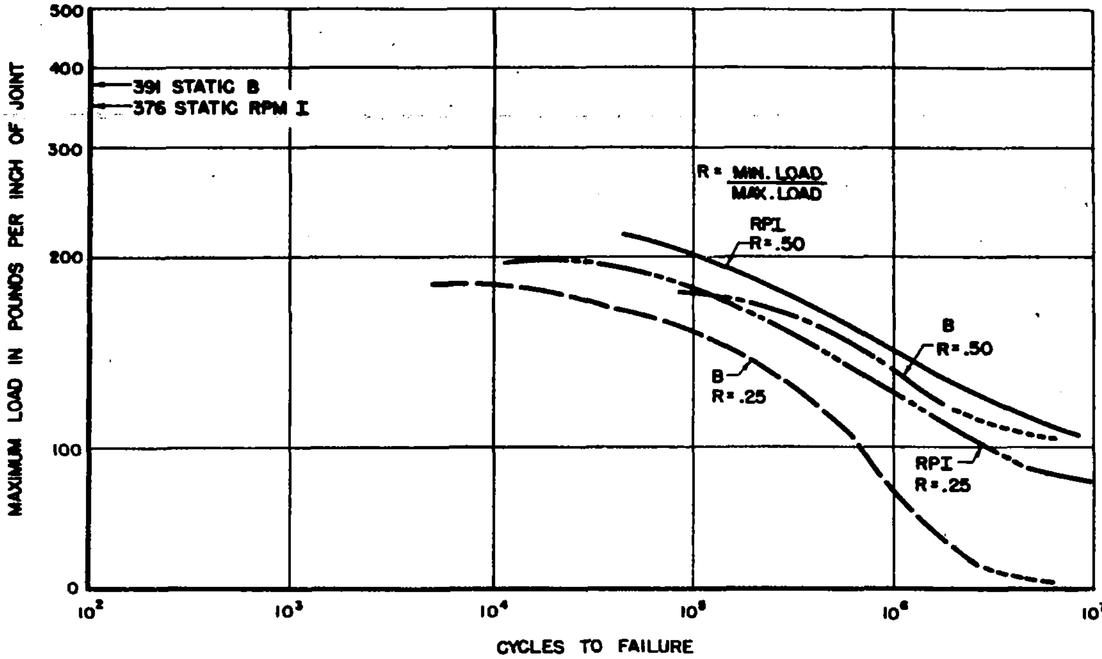



FIG.20-FATIGUE CURVES FOR LAP JOINT SAMPLES SPOT WELDED BY COMPANY B AND SAMPLES SPOT WELDED BY RPI, 0.025" SHEET, 3/4" SPOT SPACING

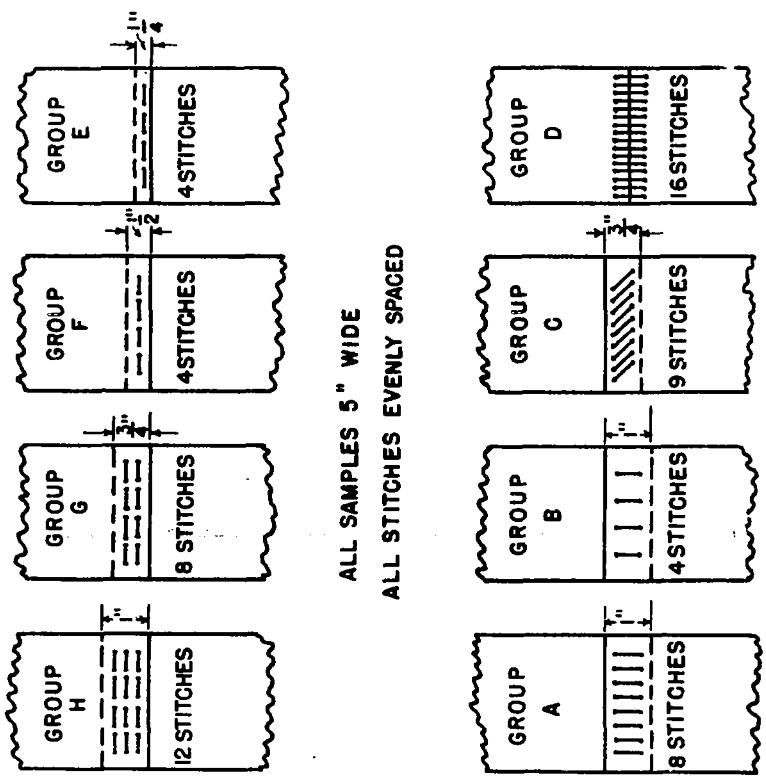
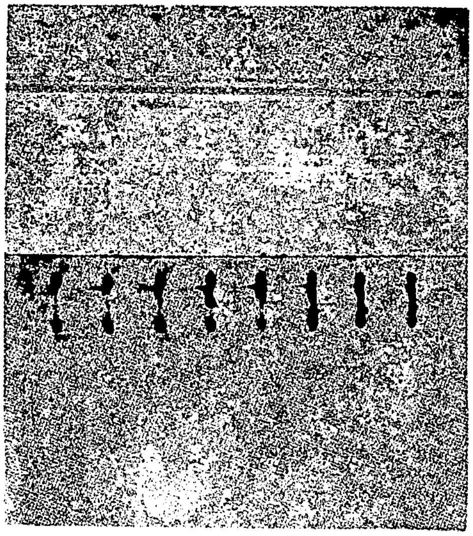
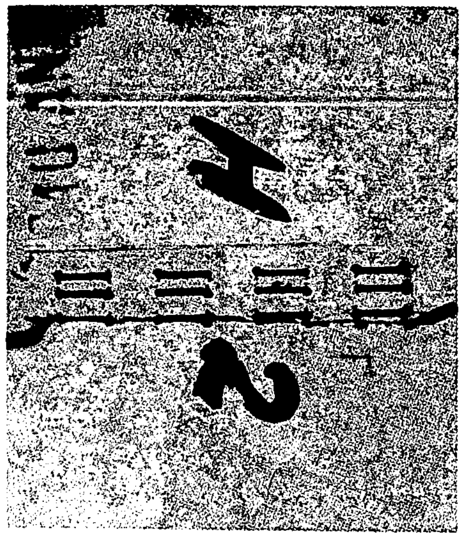



FIG.21—STITCHED LAP JOINT SAMPLES

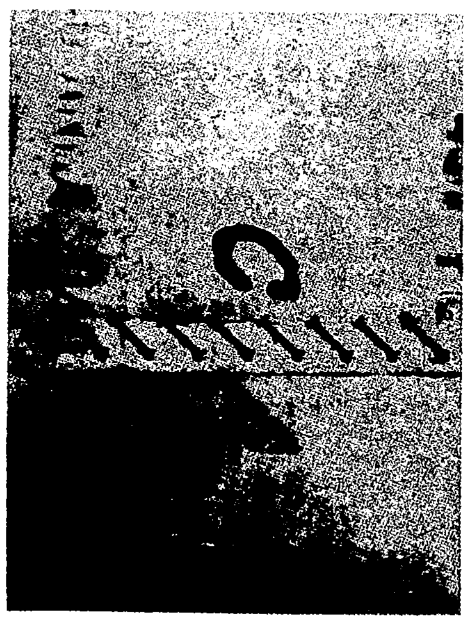


Type A
Note failure by shear of stitches.



Type H
Note crack in sheet.

Type G
Note crack in sheet.



Type C
Note crack in sheet.

22144

Figure 21a. Photographs of Stitched Joints Which Showed High Fatigue Strength.

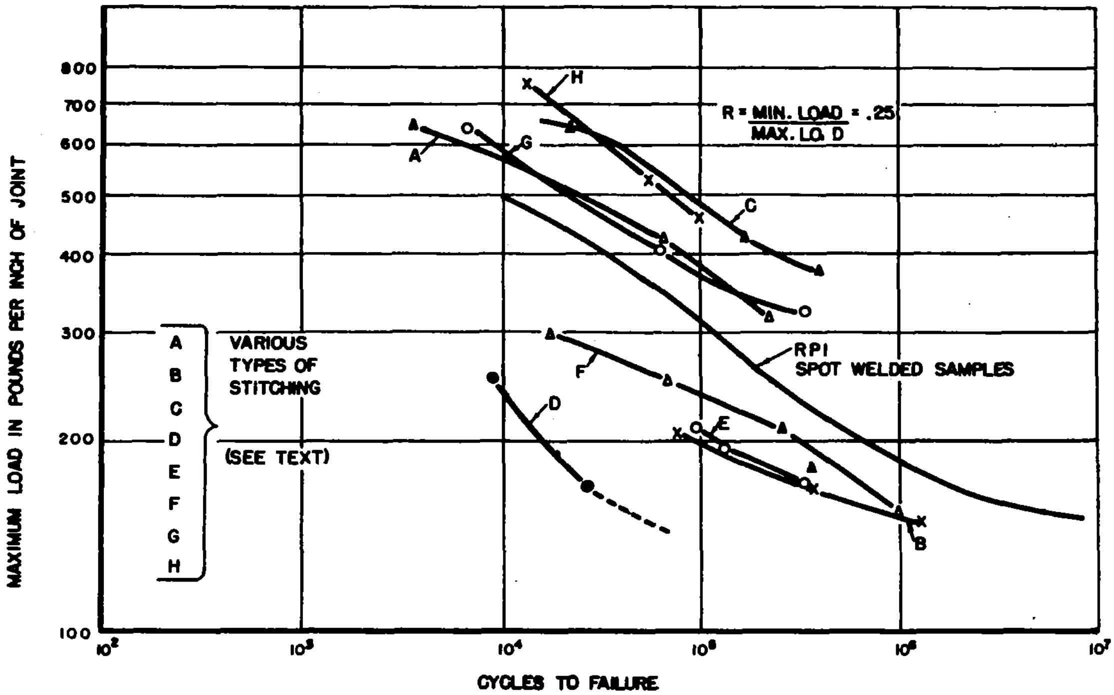



FIG. 22 FATIGUE CURVES FOR WIRE-STITCHED LAP JOINT SAMPLES OF 0.040 IN. 24S-T ALCLAD SHEET. (NOTE CURVE FOR SAMPLES SPOT WELDED AT RPI WITH 3/8 IN. SPOT SPACING.)

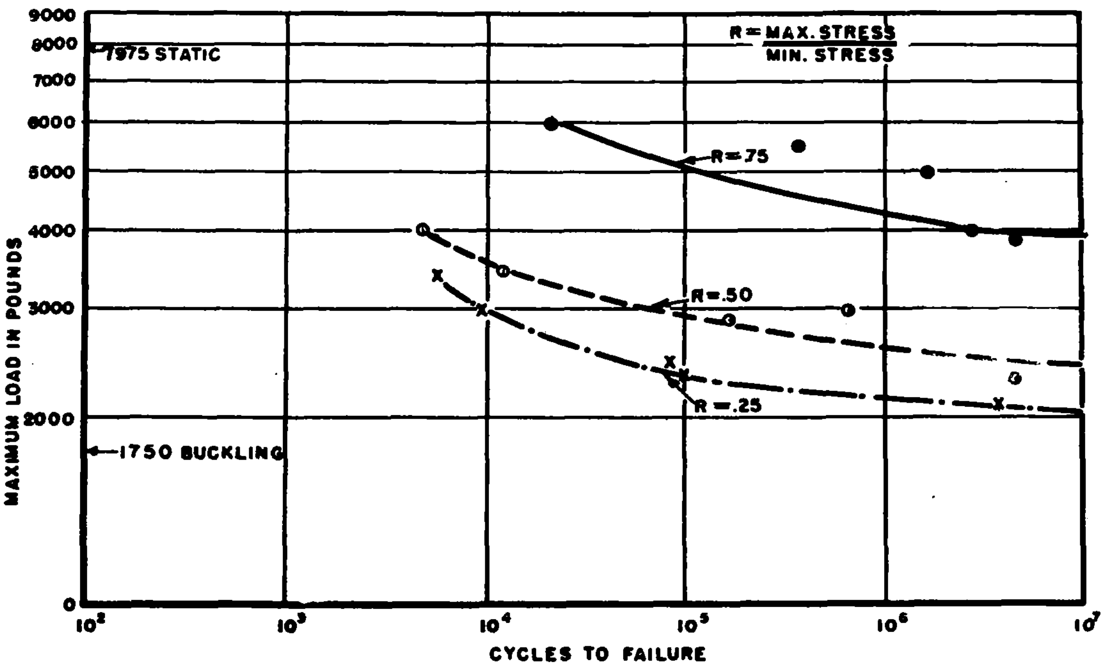
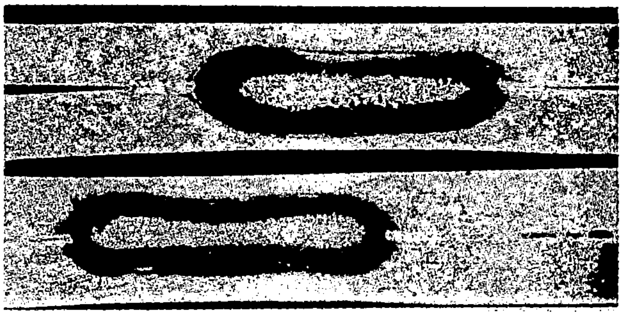



FIG. 24 COMPRESSION FATIGUE CURVES FOR STIFFENED PANELS 0.032" THICK WITH SPOTWELDS SPACED 2" APART.



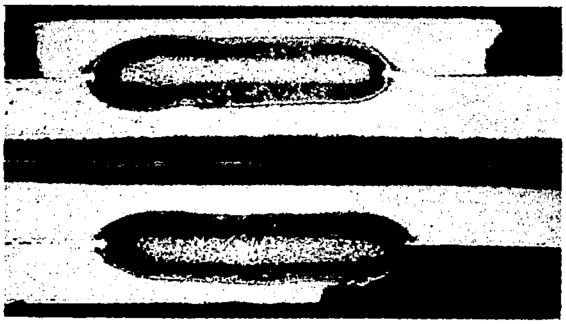
(a) Unaffected Spot Weld

(b) Small fatigue crack in weld which has not failed completely.

Keller's Etch

10X

Welds Away From Break



(c) Cracking in sheet next to weld failure.

(d) Fatigue failure in weld.

Keller's Etch

10X

Fatigue Breaks

Figure 23.

Spot Welds in 0.032" - 0.032" Stiffened Panel Sample with Spot Welds spaced 2" Apart.

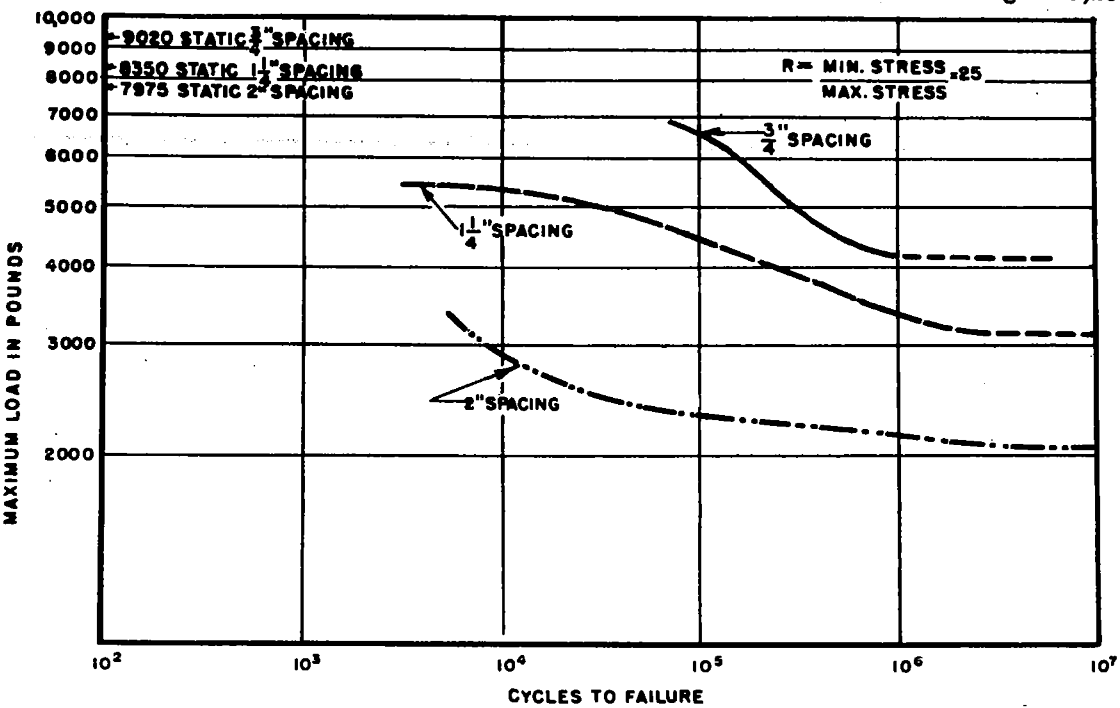



FIG. 25-COMPRESSION FATIGUE CURVES FOR STIFFENED PANELS 0.032" THICK WITH VARIOUS SPOT WELD SPACINGS.

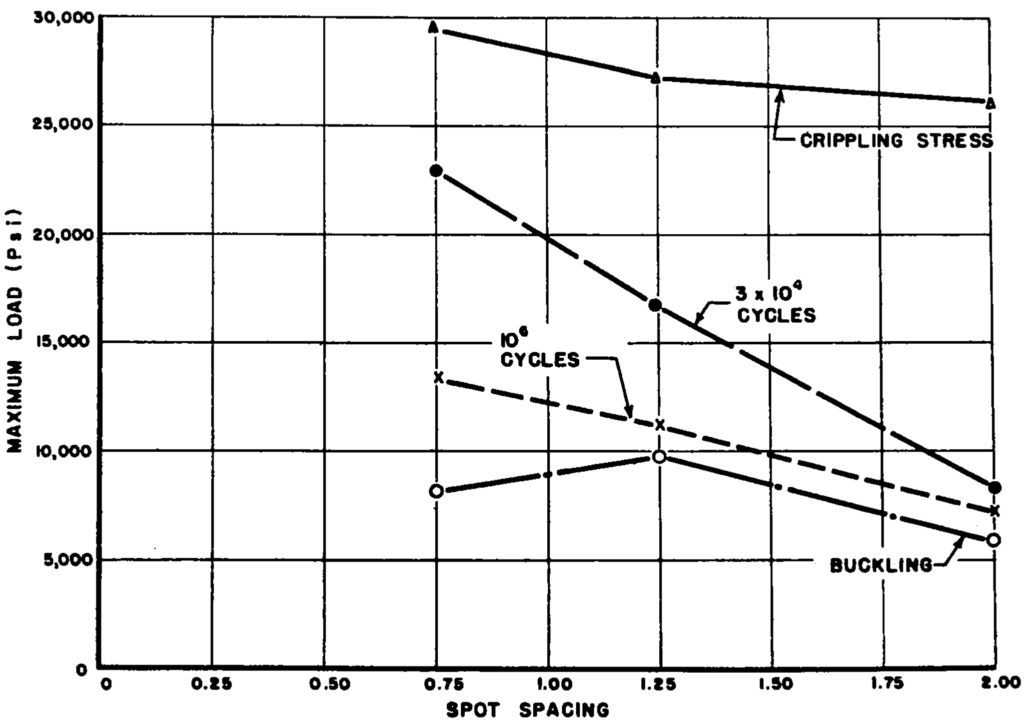



FIG. 26— EFFECT OF SPOT SPACING ON FATIGUE STRENGTH AND STATIC STRENGTH OF STIFFENED PANELS 0.032".

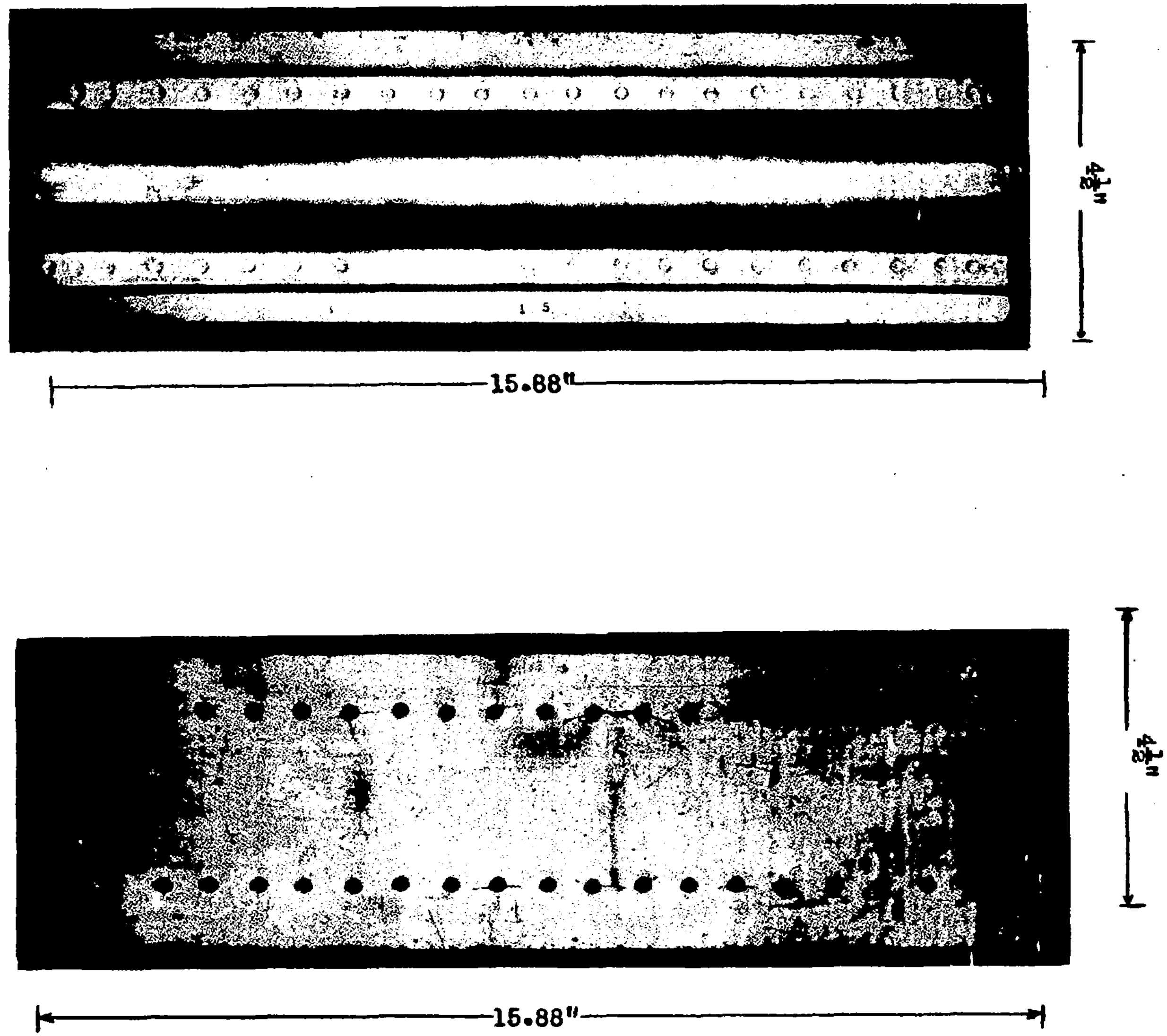
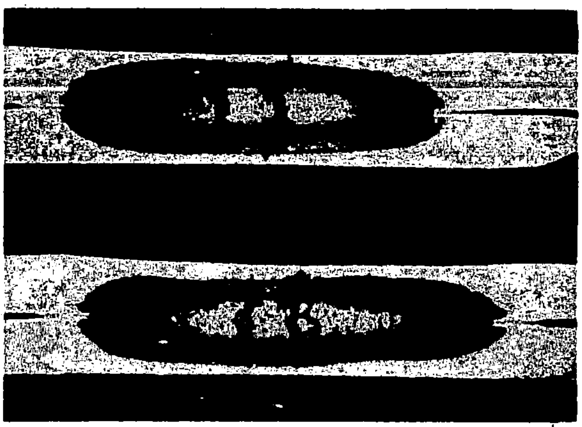



**Figure 27. Typical Stiffened Panel Sample**
**(Panel 0.040" thick, cracked spot welds spaced 3/4" apart.)**



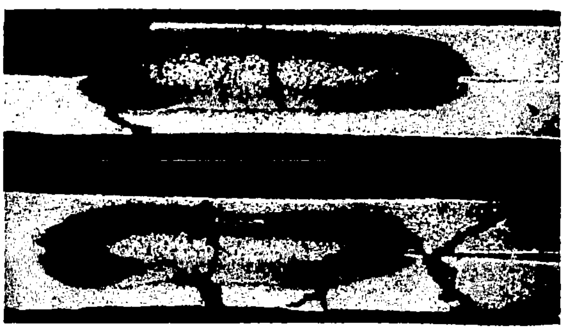
(a) Sectioned transverse to length of sample.

(b) Longitudinal.

Keller's Etch

10X

Welds unaffected by testing.



(c) Transverse.

(d) Transverse.

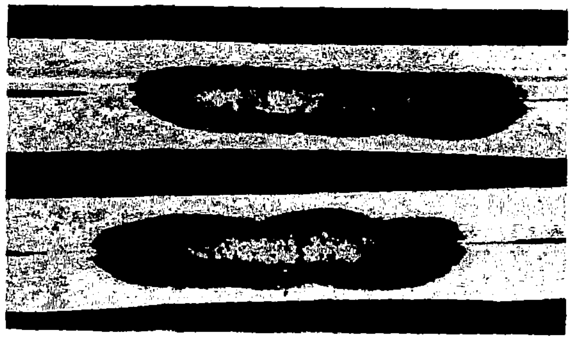
Keller's Etch

10X

Fatigue breaks.

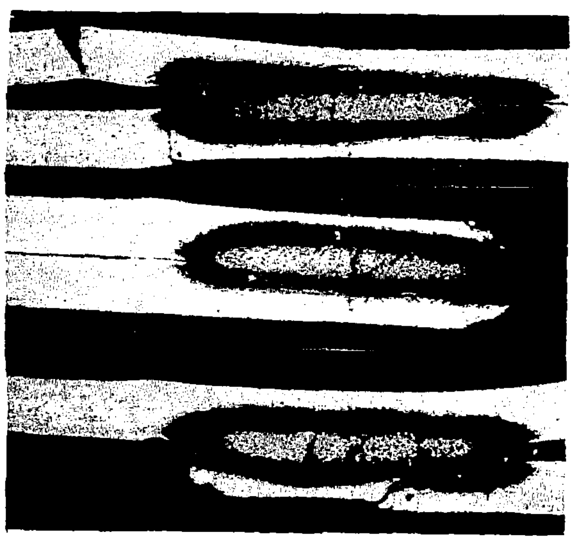
Figure 28.

Overheated Spot Welds in 0.032" - 0.032" Sheet, 3/4" Spacing, Hat-Shaped Stiffened Panel.




Keller's Etch 22102
10X

Welds Unaffected by Testing.

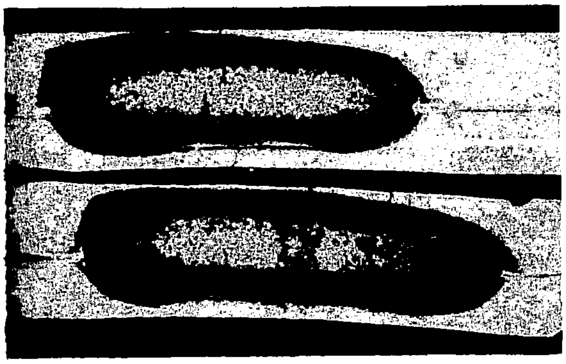



Keller's Etch 22103
10X

Fatigue Breaks.

Figure 29.

Overheated Spot Welds in 0.032" - 0.032" Sheet, $1\frac{1}{4}$" Spacing, Hat-Shaped, Stiffened Panel.



(a)

(b)

Keller's Etch 10X
22104

Welds unaffected by testing.

(c)

(d)

(e)

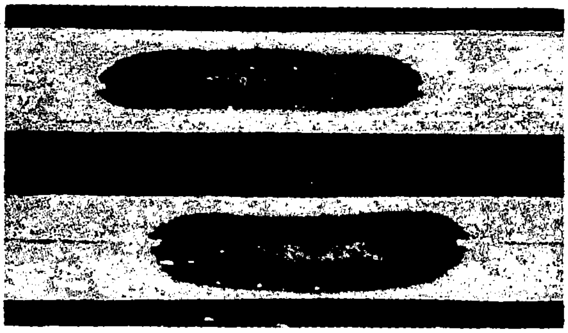
(f)

Keller's Etch 22105
10X

Fatigue breaks.

Figure 30.

Overheated Spot Welds in 0.040" - 0.032" Sheet, 3/4" Spacing, Hat-Shaped, Stiffened Panel.

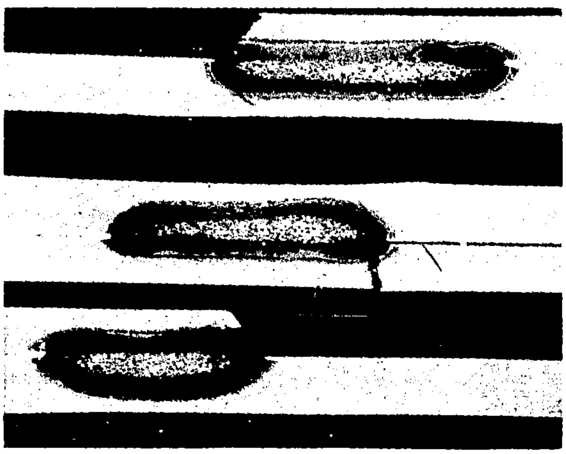


(a)

(b)

Welds unaffected by testing.

Keller's Etch 22106
10X



(c)

(d)

(e)

Fatigue breaks.

Keller's Etch 22107
10X

Figure 31.

Overheated Spot Welds in 0.025" - 0.032" Sheet, 3/4" Spacing, Hat-Shaped, Stiffened Panels.

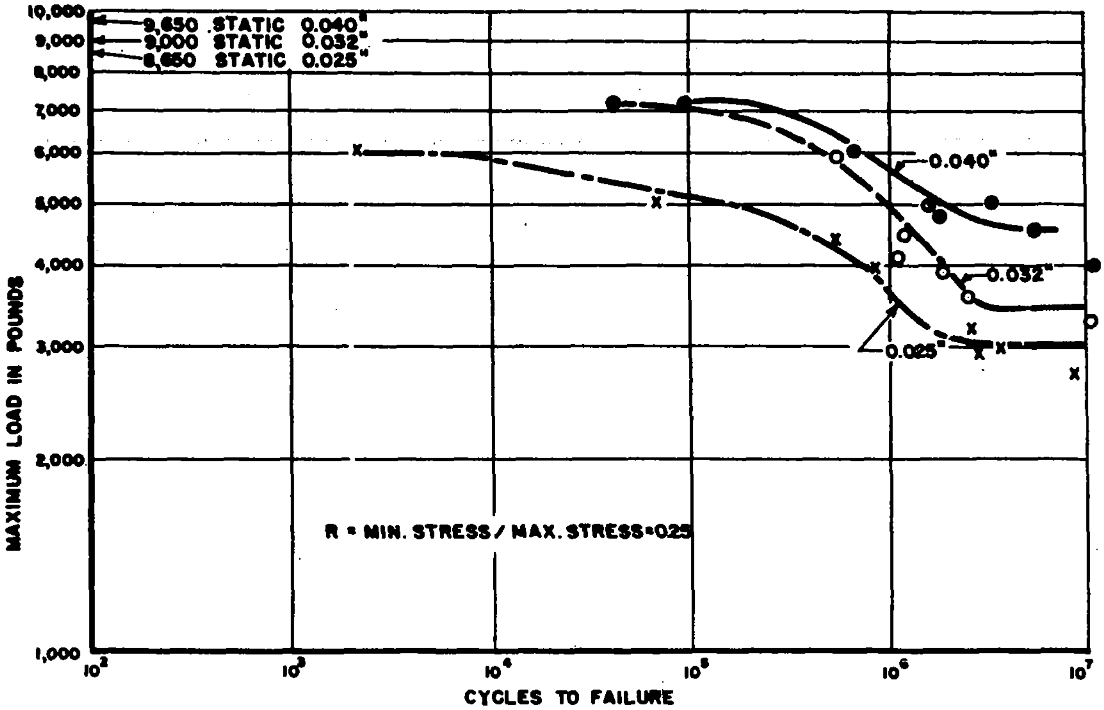



FIG. 32 — COMPRESSION FATIGUE CURVES FOR STIFFENED PANELS WITH CRACKED SPOT WELDS SPACED 3/4" APART.

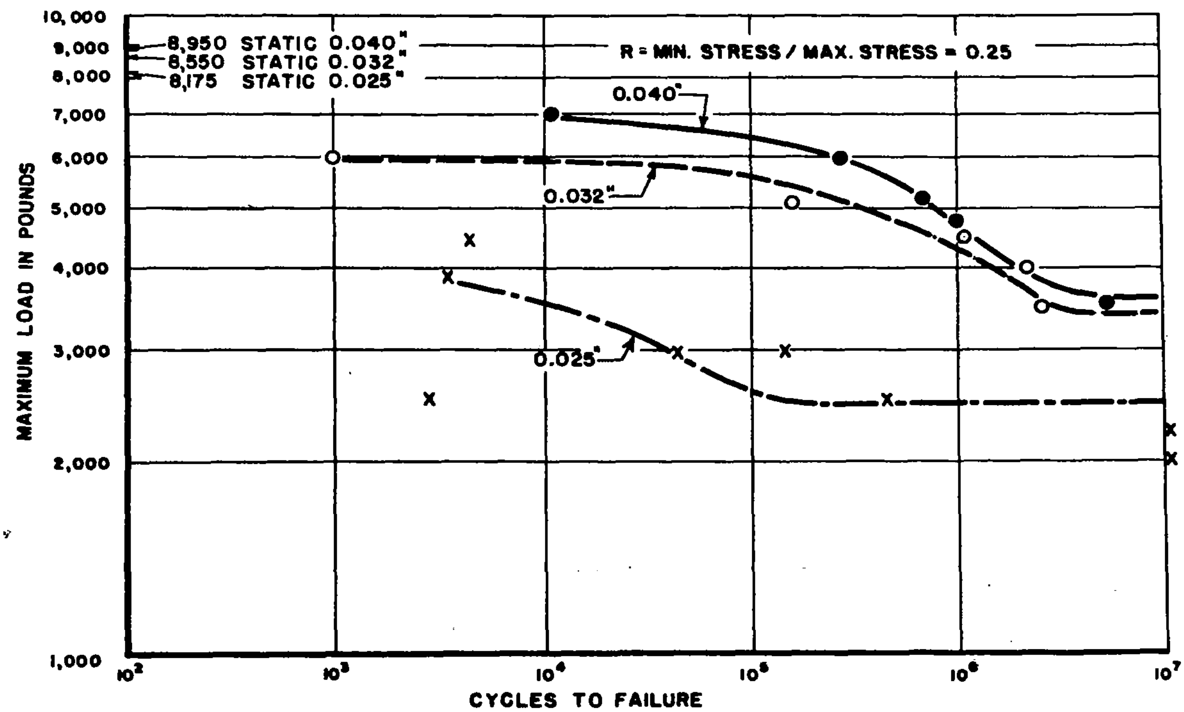



FIG. 33 — COMPRESSION FATIGUE CURVES FOR STIFFENED PANELS WITH CRACKED SPOT WELDS SPACED $1\frac{1}{4}$" APART.

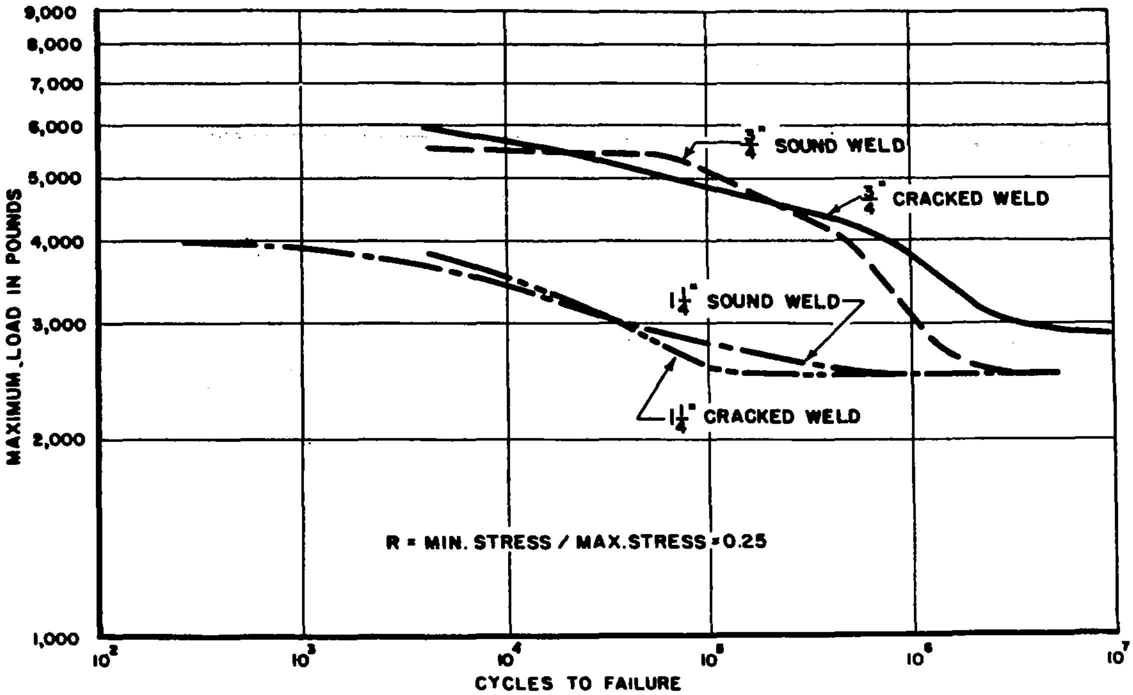



FIG. 34 — COMPARISON CURVES FOR CRACKED AND SOUND WELDS ON STIFFENED PANELS 0.025".

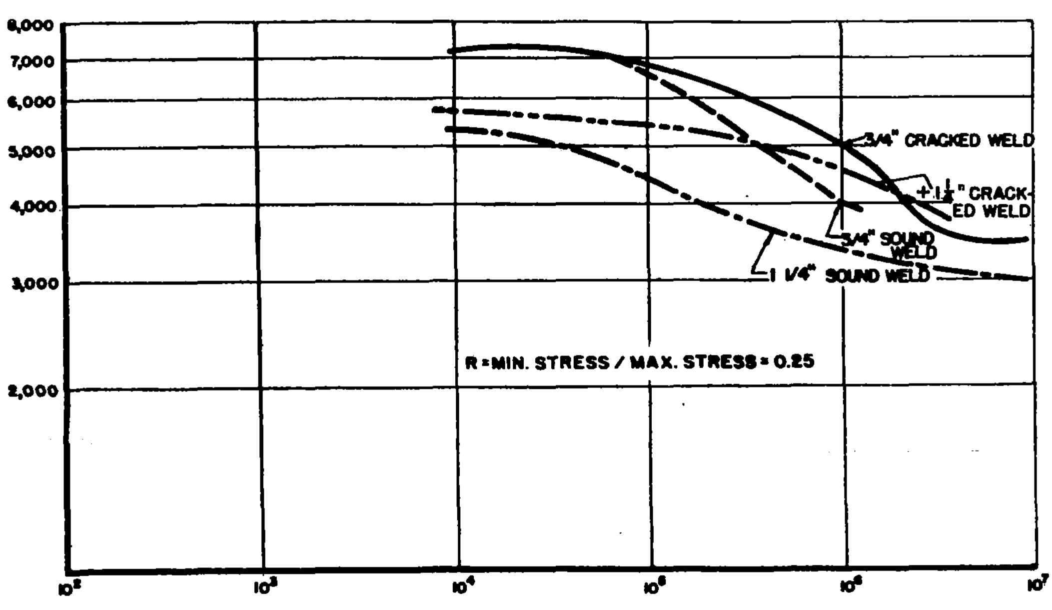



FIG. 35 – COMPARISON CURVES FOR CRACKED AND SOUND WELDS ON STIFFENED PANELS 0.032"

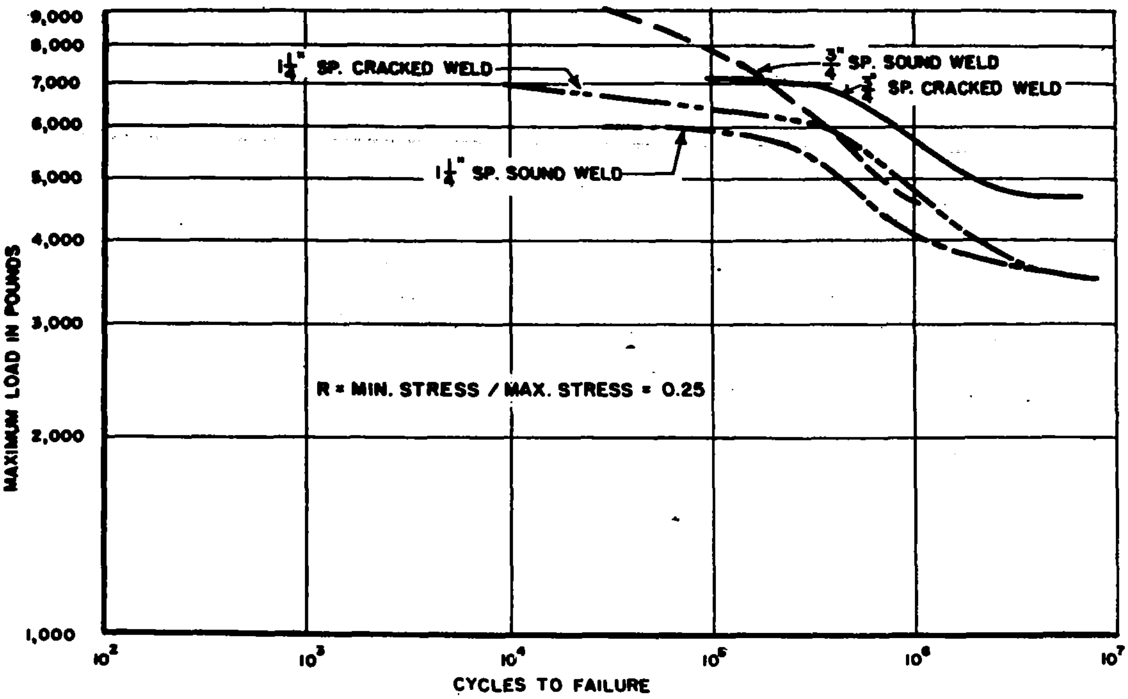



FIG. 36 — COMPARISON CURVES FOR CRACKED AND SOUND WELDS ON STIFFENED PANELS 0.040"

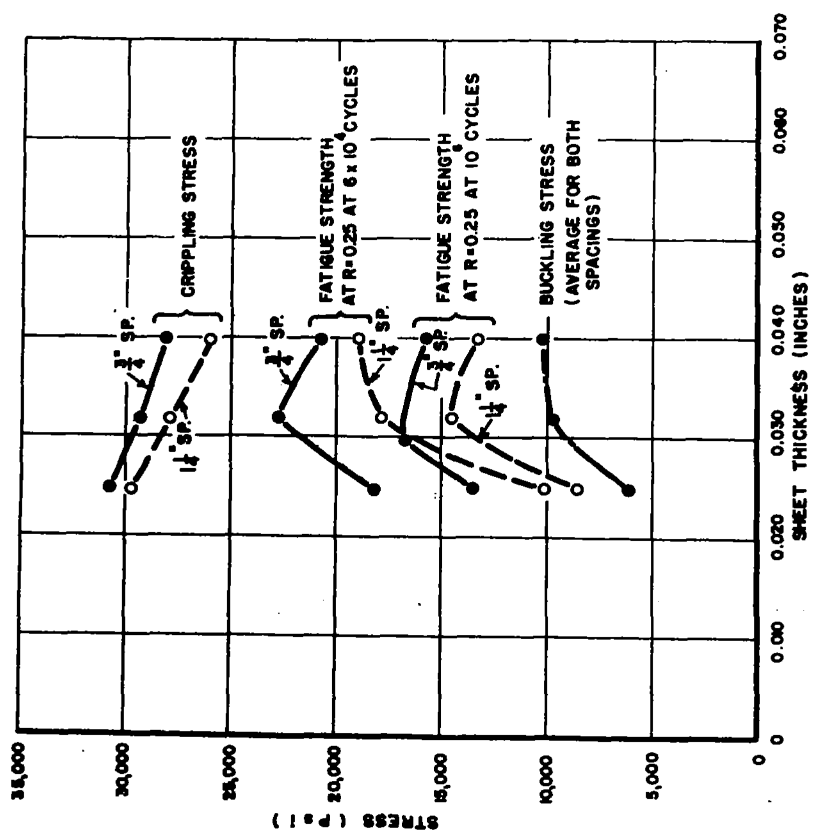



FIG. 37 — COMPARISON OF FATIGUE AND STATIC STRENGTHS OF STIFFENED PANELS WITH CRACKED WELDS.

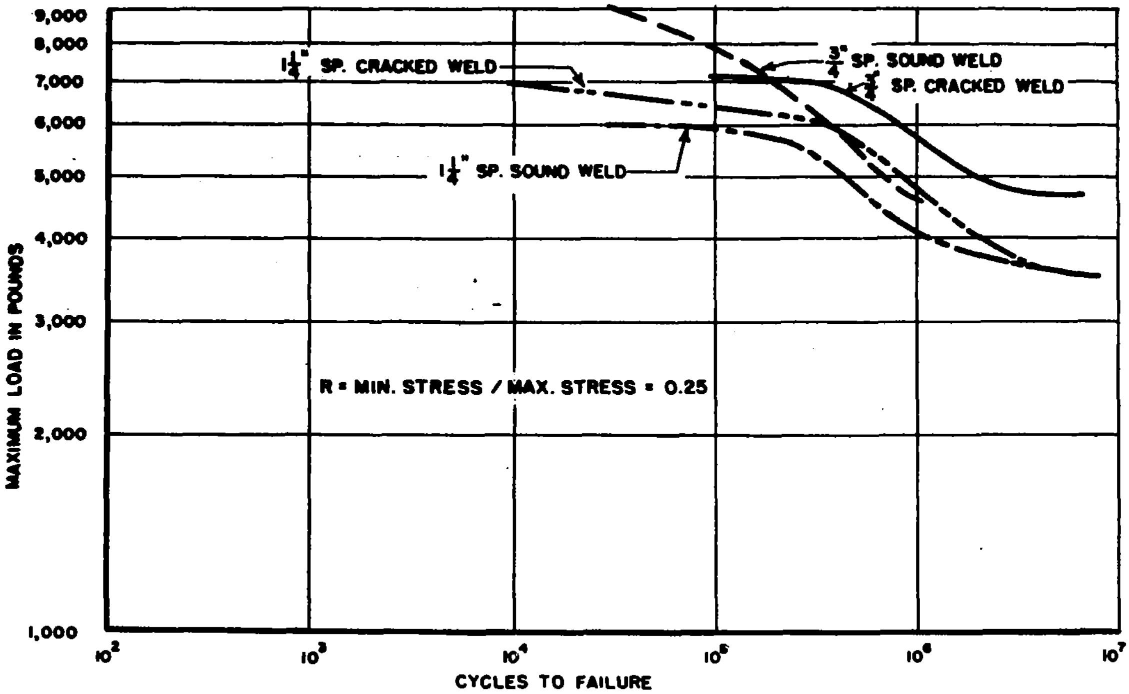



FIG. 36 — COMPARISON CURVES FOR CRACKED AND SOUND WELDS ON STIFFENED PANELS 0.040"

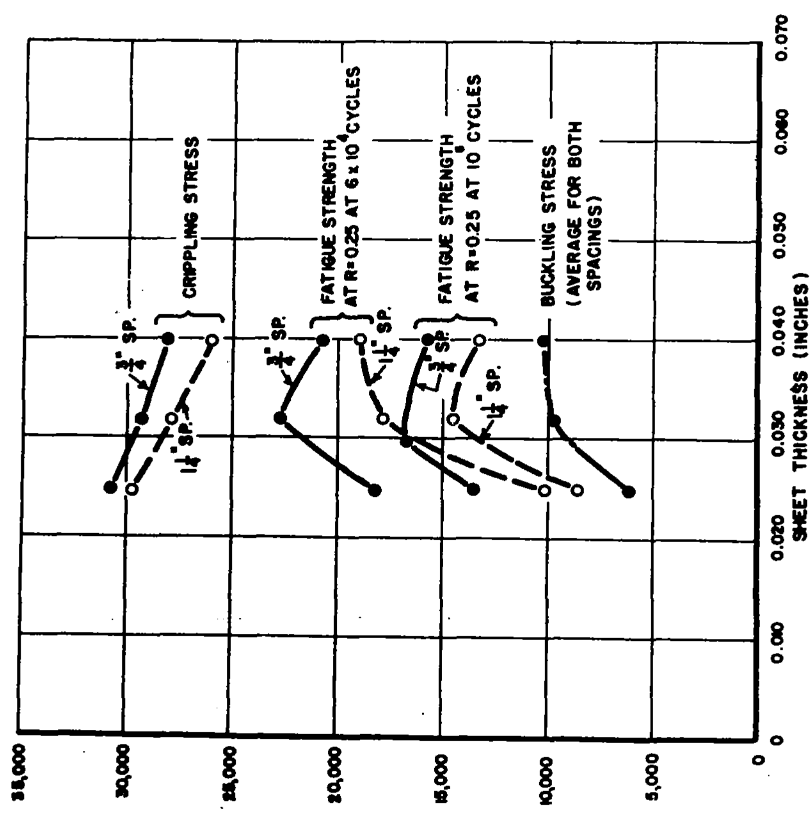



FIG. 37 — COMPARISON OF FATIGUE AND STATIC STRENGTHS OF STIFFENED PANELS WITH CRACKED WELDS.